Geochemistry and tectonic setting of Matakaoa Volcanics (East Coast Allochthon, New Zealand); supra-subduction zone affinity, regional correlations and origin.

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Abstract

In north-eastern New Zealand, the Late Cretaceous to Eocene submarine volcanic rocks of the East Coast Allochthon referred to as Matakaoa Volcanics formed a dominantly mafic melange with minor abyssal sediments during the subduction of "oceanic" crust. Accreted and melanged pillow lavas and dolerites display the geochemical and isotopic features of tholeiites with some diversity referred to as mid-ocean ridge basalts, island-arc tholeiites and back-arc basin basalts. The association of supra-subduction tholeiitic magmas, abyssal sediments and polymetallic volcanogenic sulphide deposits is typical of many back-arc basins; therefore, a correlation with the alkaline and transitional basalts of the Hikurangi-Manihiki-Ontong Java Plateau may be ruled out. These petrological features and the fossil ages as well, are closely similar to those of the Tangihua Complex (Northland Allochthon) and allow Matakaoa and Tangihua mafic volcanic rocks, now separated by the modern Havre Trough, to be correlated within one single Late Cretaceous to Eocene basin. The consideration of possible younger ages (Oligocene) is also discussed. The occurrence of Late Cretaceous-Eocene "oceanic" crust with supra-subduction zone affinities to the east of the Norfolk Ridge poses the problem of the intervening southwest-dipping subduction, the missing Late Cretaceous-Eocene arc and their relationship with Southeast Gondwana marginal break-up.

Key words: New Zealand, Southwest Pacific, Late Cretaceous-Eocene, back-arc basins, subduction, peel-off mélange.

Introduction

The evolution of the Southwest Pacific apparently underwent a marked change from the active margin setting that prevailed during the Early Permian to Early Cretaceous into the widespread and synchronous marginal basins opening that isolated large slices of the south-eastern Gondwana margin during the Late Cretaceous and Paleocene (ca. 90-55 Ma). These continental fragments now form New Zealand, New Caledonia and their undersea extensions, the Lord Howe Rise and Norfolk Ridge (Fig. 1). The end of the long-lived active margin activity in the New Zealand part of southeast Gondwana at ca. 100 Ma (Laird and Bradshaw, 2004) is probably due to the collision of the Hikurangi Plateau with the active margin at ca. 105 Ma (Hoernle et al., 2004; Mortimer et al., 2006; Davy et al., 2008) although some uncertainty remains about the precise timing of active margin extinction (Mortimer, 2004). In contrast, the driving mechanism of the marginal break-off is still debated and many hypotheses have been considered: i) marginal rifting triggered by a mantle plume (Bryan et al., 1997); ii) subduction of a spreading ridge (Mortimer et al., 2006); or, iii) marginal basin opening controlled by eastward slab roll-back and arc migration in a continuously converging environment (Lister and Etheridge, 1989; Veevers et al., 1991, Cluzel et al., 1999; Veevers, 2000a,b; Cluzel et al., 2001; Betts et al., 2002; Schellart et al., 2006). Thus, the nature of the magmas that have been generated in the Southwest Pacific during the Late Cretaceous and Paleocene is crucial to constrain its geodynamic evolution. However, most of the geologic evidence is now below sea level and the bulk of relevant information is restricted to the mafic allochthons of northern New Zealand and New Caledonia.

A feature of the mid-Tertiary geology of the northern and eastern parts of the North Island is the occurrence of extensive tracts of sedimentary and volcanic material of Cretaceous to Oligocene age that were thrust and/or slid onto the in-place Mesozoic basement and its early Tertiary sedimentary cover in the earliest Miocene. The oldest but uppermost part of the allochthons consists of disrupted pillow-lavas, dolerites, and associated abyssal sediments of Late Cretaceous to early Eocene age. These thrust complexes are known as the East Coast and Northland Allochthons (Fig. 2) and the mafic rocks contained within them as the Matakaoa Volcanics and the Tangihua Complex respectively. While the Tangihua Complex rocks have been subjected to detailed geochemical and geochronological studies in recent years (Nicholson et al., 2000 a, b; Whattam et al., 2005, 2006), the Matakaoa rocks are poorly known and except for the recent paper of Brathwaite et al (2008) there has been no geochemical data for them. In this paper, we describe the geochemical and isotopic features of Matakaoa Volcanics, and compare them to the mafic rocks of the Tangihua Complex, in order to establish correlations and discuss the tectonic conditions that were involved in their generation and emplacement.

Nature and geological setting of the Matakaoa Volcanics.

The East Coast Allochthon forms a 120 km long SSW trending lobe that is exposed over a large part of north-eastern North Island (Raukumara Peninsula; Fig. 3). It is formed of sliced sediments (Late Cretaceous-Oligocene) that are not dissimilar to the autochthonous basement on one hand, and mafic volcanic rocks and pelagic/abyssal sediments (the Matakaoa Volcanics) of undoubtedly “oceanic” origin on the other. The allochthon is covered by the overlying Miocene-Pliocene sequence and is almost certainly more extensive at depth (Mazengarb and Speden, 2000). The Matakaoa Volcanics which form two massifs (Mangaroa and Pukemaru) separated by a Neogene graben (Fig. 3), are considered to be the oldest but uppermost and hindmost parts of the East Coast Allochthon that was emplaced in the earliest Miocene.

The bulk of Matakaoa Volcanics is formed of sliced massive and pillowed basalt associated with hyaloclastite; pelagic or abyssal sediments, and many small-scale mafic hypabyssal bodies. Volcanic breccia of basaltic to andesitic composition with angular gabbro boulders and tachylite are not uncommon and suggest explosive eruption, or almost synchronous tectonics and/or submarine collapse. No evidence for tidal zone or sub-aerial evolution such as rounded pebbles or shallow water fossils may be reported. Basalts may be either fresh; or alternatively, affected by low temperature alteration (ocean floor metamorphism ?). The general attitude is upright, generally top-to-the-north but in detail, there is no continuity and slices are commonly separated by strike-slip faults. Near the boundary with Pukemaru Massif (Fig. 3), the overlying Late Miocene marl and limestone locally pass into monogenetic matrix-supported cobble conglomerates. The occurrence of cm to dm scale angular blocks of basalt included within a marine limestone matrix suggests the existence of basalt cliffs at the time of sediment deposition (rock fall deposits at the base of Miocene fault scarps?) rather than a tidal or sub-aerial environment. In addition, in the vicinity of the two massifs, cobbles of Matakaoa Volcanics are enclosed in Miocene and in many other late Tertiary sediments throughout Raukumara Peninsula (e.g. Black, 1980; Kenny, 1984).

While the Matakaoa Volcanics in the Mangaraoa Massif have good coastal exposures, the inland Pukemaru Massif is poorly exposed and thus much less well known; it seems to be mainly composed of massive basalt, scarce intrusive rocks and pillow lavas with no, or only a few, associated sediments.

Sediments are abundant in the Matakaoa Volcanics with lenses and slivers having an apparent thickness of a few tens of cm to 100s of metres (max about 800 m). There is a considerable variety of sedimentary lithologies including shale and mudstone (green, grey or purple), red and green chert, cream siliceous volcanogenic siltstone and pink micrite. All these lithologies are consistent with pelagic or abyssal environments. The pillow lavas rarely have interpillow material but when it does occur it is usually limestone rather than chert. Assessing the time relationship of volcanics and associated sediments is not always possible because of the high degree of tectonic disruption of most outcrops; however, in a few less deformed locations, clear sedimentary contacts may be observed between submarine volcanic rocks and deep water sediments. Pink pelagic limestone often contain glass shards and tiny basalt clasts; in addition, basalt intrusion within unconsolidated and water saturated sediments have been observed by previous authors (e.g. Gifford, 1970; Strong 1976, 1980) providing robust evidence for syn-depositional relationship. Some of the sediments are fossiliferous, and macrofossils (*Inoceramus*) have been recorded on the west side of Cape Runaway, together with a radiolarian and foraminifera micro-fauna that indicate a Late Cretaceous age (Strong, 1976). On the western side of Lottin Point, radiolarian and foraminifera assemblages in sedimentary inliers also indicate a Late Cretaceous age for the IAT-like basalts (see below) that are closely associated with them. However sediments between these two localities contain Paleocene to mid-Eocene foraminifera and radiolarian faunas; thus, MORB-like basalts that rest below Paleocene sediments to the south-east of Cape Runaway have most probably the same age (Fig. 3). Foraminifera from sedimentary float in the Pukemaru Massif indicate that rocks in this massif also have Paleocene - Eocene ages (Strong, 1980).

The coastal succession of Mangaroa has been affected by km-scale gentle steeply plunging folds associated with semi-brittle wrench faulting (Spörli and Aita, 1994). Sedimentary inliers are often severely disrupted, boudinaged and display melange features. It is worth noting that melange only contains Late Cretaceous-Eocene pelagic or bathyal sediments and no terrigenous or younger sediments have been hitherto reported.

The Matakaoa Volcanics show a significant range of igneous material which includes basaltic hyaloclastites, tuffs, massive and pillowed lavas, and doleritic intrusives. Lava and dolerite compositions are mainly basaltic. The lavas are mainly non-vesicular dominantly augite-pyroxene basalts with little interpillow material and pillow breccia complexes. There are some substantial exposures in the middle of the massif, on the west side of Lottin Point and in the Matakaoa Point area, composed of resedimented hyaloclastite (tachylite), and basalt – dolerite – gabbro breccias which also contain tachylite blocks. The breccias are locally hydrothermally altered and contain abundant prehnite (and less commonly pumpellyite). Prehnite also appears in early veins (sometimes with quartz) crosscut by zeolite veins with laumontite, or analcime + natrolite + stilbite, the last veins in all cases containing calcite. Dykes and gabbros cut the pillow complex sequences and the breccias. Olivine is not common in the basalts where it usually occurs as chloritised relics; however some fresh olivine-rich rocks, called picrites by earlier workers (Gifford, 1970; Rutherford, 1980; Pirajno, 1980), occur together with olivine gabbros and "teschenites" (actually amphibole-bearing sub-alkaline rocks) in a fault bounded block near Lottin Point. Dolerite dykes are common cutting all the volcanic lithologies including the breccias and the picrite – gabbro – "teschenite" complexes (Pirajno, 1980).

Geochemistry

A collection of 39 samples of predominately volcanic and minor intrusive rocks from the Matakaoa Volcanics have been analysed for major oxides, trace and rare earth elements. This has enabled a characterization and recognition of magma sources not possible in previous studies. The locality and chemical affinity details are given for representative samples in Table 1 and their major, minor and trace element data in Table 2.

***Sample preparation**: External surfaces of fresh rocks were removed by splitting and the samples split into chips which were then ground to a powder in a tungsten carbide ring grinder. $H2O^+$, $H2O^-$ were determined by gravimetry, the remaining major oxides and trace elements were first determined by XRF (after Norrish & Chappel, 1977) at the University of Auckland, New Zealand. The precision (2σ) of the major oxide determinations is generally less than 2%, and less than 5% for the trace elements at ten times the detection limit of 1-2 ppm. HFS and rare earth element abundances were secondly determined by inductively coupled plasma mass spectroscopy (ICP-MS) at the Laboratoire de Géodynamique des Chaines Alpines, Université Joseph Fourier, Grenoble, France (UMR 5025) using the method of Barrat et al. (1996). The precision ($2\ \sigma$) for ICP-MS analyses varies from 2-10% for the elements analysed as determined using the standards BHVO and Br24 (Barrat et al., 1996). Nd and Sr isotopic ratio were determined using mass spectrometry in Toulouse University (France) after separations on columns in LGCA – Grenoble University.*

In the following paragraphs, although the difference is nowhere meaningful, (X/Y)nC represent elemental ratios normalised to the chondrite, and (X/Y)nM elemental ratios normalised to the average MORB. The following abbreviations will be used throughout the text: MORB: Mid-Oceanic Ridge Basalt; N-MORB: Normal MORB; T-MORB: Transitional MORB; E-MORB: Enriched MORB; IAT: Island-Arc Tholeiite; BABB: Back-arc Basin Basalt; CAB: calc-alkali Basalt; OIB: Ocean Island Basalt; LILE: Large Ion Lithophile Element; HFSE: High Field Strength Element; LREE: Light Rare Earth Elements; HREE: Heavy Rare Earth Elements.

The presence of alteration is normally reflected in the abundances of the more mobile elements and LOI (loss of ignition), and only two samples present LOI > 4% (LOI = 4.43 and 7.45); so, 39 samples with total volatile content < 4wt% were chosen for the study of Matakaoa volcanic rocks (Table 1). With regard to major elements composition, lavas and dolerites are mainly basaltic (SiO_2 = 47-53 wt %) with medium to low MgO contents (7.5-1.7 wt%), and some rare silica-rich rocks (SiO_2 = 55.8-60.3 wt%, MgO = 4.5-3.3 wt%) occur in the north of the Matakaoa Massif. However, an alkali-silica (not presented) or alkali-MgO plot (see annex I) shows a prominent scatter in the total alkali content that contrasts with the relatively narrow field in which Matakaoa Volcanics plot on classification diagrams based upon "immobile" trace elements, indicating that the effects of alteration on mobile elements have to be considered and that rock classification should not be established upon them. On the Zr/TiO_2 vs. Nb/Y classification diagram (Winchester and Floyd, 1977) which is used instead of the total alkali vs. silica diagram in the case of metamorphic or slightly altered rocks, the Matakaoa Volcanics plot within the field of andesitic basalts with only some scatter of the "alkalinity ratio" represented by Nb/Y (Fig 4). In addition, the Zr/TiO_2 ratio is not correlated with SiO_2 variation; therefore, high SiO_2 contents are likely to be a secondary feature. It is worth noting that the typology established on the basis of REE contents and Nb-Ta depletion (see below) is fully consistent with the variation of the Nb/Y ratio. Similarly, on the Th/Yb vs Ta/Yb diagram (Pearce, 1983) (Fig 5), the Matakaoa Volcanics have similar Th/Yb ratios consistent with the high degree of melting of a moderately depleted mantle source, but may be distinguished upon the variation of the Ta/Yb ratio (equivalent to Nb/Y) into uncontaminated (MORB-like), poorly contaminated (BABB-like) and contaminated (IAT-like) basalt types. Two samples which have Ta/Yb > 0.1 will be thereafter referred to as "transitional basalt" (TB in figure captions).

The Matakaoa basalts and dolerites are all strongly depleted in LREE ((La/Sm)nC = 0.48 to 0.79; (La/Yb)nC = 0.47-1.0) (Fig. 6a), a feature that suggests a depleted shallow mantle source. However, they show variable LILE contents and also a variable Nb–Ta depletion ((Nb/La)nM = 0.37 to 0.97; (Ta/La)nM = 0.45 to 1.19) (Fig. 6b). These features suggest the coexistence of lavas types similar to mid-oceanic ridge basalt (MORB-like), back-arc basin basalts (BABB-like) and island arc tholeiites (IAT-like) that can be distinguished as follows:

- MORB-like volcanics (SiO_2 = 47.7-50.6 wt%, MgO = 4.98-7.55 wt%) are depleted in LREE ((La/Sm)nC = 0.55-0.79, ((La/Yb)nC = 0.68-1.0) with relatively high TiO_2 contents (1.75-2.73 wt%). They show moderate LILE enrichment, almost no Nb-Ta depletion ((Nb/La)nM = 0.73-0.97 and (Ta/La)nM = 0.81-1.19), and are characterised by high Nb/Th ratios (12.8 -17).

- BABB-like volcanics (SiO_2 = 48.5–50.2 wt%, MgO = 6.26-9.06 wt%) are also strongly depleted in LREE ((La/Sm)nC = 0.55–0.75; ((La/Yb)nC = 0.62-0.89). They show lower TiO_2 contents (1.35-1.79 wt%), intermediate Nb-Ta depletion ((Nb/La)nM=0.56–0.72; (Ta/La)nM = 0.70-0.93) and Nb/Th ratio 9 to 14.
- IAT-like basalts have medium TiO_2 (1.05-1.73 wt%) and MgO (3.31-7.08 wt%) contents, and variable SiO_2 (48.2 to 60.3 wt%). They are all enriched in LILE and show LREE and Nb-Ta depletion ((La/Sm)nC = 0.48-0.72; (La/Yb)nC = 0.47-0.84; (Nb/La)nM = 0.37-0.62; (Ta/La)nM = 0.44-0.74). They typically display the lowest Nb/Th ratios (4.7 to 9.5).
- andesitic basalts transitional towards alkali basalt (two samples only) hereafter referred to as TB (transitional basalt) typically display higher Nb/Y ratios, high TiO_2 and much higher LREE contents compared with the rest of Matakaoa Volcanics.

The three main geochemical types are petrographically very similar and cannot be distinguished in the field; however, the IAT are usually porphyritic (augite and plagioclase phenocrysts) and the rare orthopyroxene recorded in the Matakaoa volcanics always occurs in the IAT. MORB-like basalts are dominated modally by clinopyroxene and are often non-porphyritic; and the BABB occasionally contain pink - brown Ti-rich pyroxene and a reddish brown hornblende. These chemically distinct rock types are found in many locations in the western part of Matakaoa massif; in contrast, IAT are the major volcanic type to the east of the massif where they occur as pillow lavas. Elsewhere in the massif, rocks of IAT affinity are dolerites and diorites which suggest that at least some of the IAT are younger than the MORB and BABB; however there is no sensible chemical difference between IAT lavas and sub-volcanic intrusions.

Magma sources and geodynamic setting

One of the most obvious features of the Matakaoa Volcanics is the continuous range of composition between IAT, MORB and BABB end-members which is very apparent on the Ta/Yb vs. Th/Yb diagram of Pearce (1983, Fig. 5), and on many other "discriminant" diagrams (not represented) this feature is also apparent on trace and rare earth element spidergrams (Fig 6). A common feature of these rocks is the depletion in LREE (Fig 6a) which is consistent with low pressure melting of depleted mantle. In contrast, the trace element abundance patterns differ with a relative depletion of Nb and Ta in BABB and lower bulk REE content (Fig 6b). Distinguishing back-arc from mid-ocean ridge basalts is possible because the depletion of Nb and Ta in BABB reflects formation from a subduction-modified mantle that contains Nb and Ta receptors such as ilmenite or pargasitic amphibole in the refractory phase. However, in the case of Matakaoa Volcanics, MORB-like lavas also show a small Nb depletion. All the rock types are variably enriched in LILE which may result either from the input of fluids derived from slab dehydration, selective extraction during hydrous melting (Langmuir et al., 2006); or, alternatively, from elemental mobility during low grade metamorphism and/or hydrothermal alteration. The occurrence of IAT is also generally associated with juvenile intra-oceanic arcs and/or oceanic basins that form in connexion with metasomatised supra-subduction mantle (Keller et al., 2008; Metcalf and Shervais, 2008). It is worth noting that Nb-Ta depletion decreases when the bulk REE content increases. The bulk REE content of basalt may be related either to the degree of partial melting; or, alternatively to fractional crystallisation; as the three rock types show no evidence for prominent differentiation, it appears that Nb-Ta depletion is correlated with a higher melting degree, which may be due to higher water content of the source, as is the case of metasomatised mantle. A close association of MORB, BABB and IAT-like basalts is thus a product of low pressure melting of a variably metasomatised mantle source in a supra-subduction environment (Marsh et al., 1980; Wood et al., 1981; Perfit et al., 1987; Vallier et al., 1991; Jenner et al., 1991).

The Nb-Ta depletion which is apparent on REE and trace elements spiderdiagrams is uncorrelated with an increase of Pb and Sr contents which are generally associated with volcanic-arc magmas (Fig. 7); therefore, a prominent input of subduction or continental crust-derived material is unlikely as emphasised by Nd and Sr isotopic ratios (see below).

ε_{Ndi} isotopic ratios of the Matakaoa volcanic rocks remain within a very narrow range of variation ($+7.06 < \varepsilon_{Ndi} < +8.12$) and plot within the depleted mantle (MORB) field (Fig. 8). In contrast, $(^{87}Sr/^{86}Sr)i$ ratios display a wider range (0.7021 to

0.7044). Moderately variable ($^{87}Sr/^{86}Sr$)i and invariable ε_{Ndi} suggest post-magmatic water-rock interaction (ocean floor metamorphism or hydrothermal alteration) rather than contamination by subducted sediments, continental crust, or subduction fluids. ε_{Ndi} values fit with a moderately depleted mantle source for these volcanic rocks which is consistent with either a juvenile intra-oceanic arc, or a back-arc environment.

Distinguishing tectonic environments on the basis of geochemistry alone is not possible because similar magma forming processes may actually occur in different settings. In the present case, a similar association could appear in an incipient arc, a back-arc or in a fore-arc setting as well; however, a close association of magmas formed from variably metasomatised sources and abyssal sediments is a feature of basins formed in an extensional setting in a supra-subduction zone environment, e.g. a back-arc basin environment (Keller et al., 2008; Metcalf and Shervais, 2008). This interpretation is compatible with that of Brathwaite et al (2008) who additionally considered the occurrence of polymetallic volcanogenic massive sulphide (VMS-type) mineralisation closely associated with Matakaoa Volcanics.

Comparison of Matakaoa and Tangihua mafic rocks

The Matakaoa and Tangihua Volcanics display significant petrographic and geochemical similarities. The comparison below is based on the dataset already published by Mortimer et al. (1998), and Nicholson et al. (1999, 2000a, b). It is worth noting that both the Matakaoa and Tangihua volcanic rocks contain MORB, BABB and IAT-like rocks with similar REE patterns and Ta-Nb depletion (Fig 9 and Fig 10) which often coexist at the same locality. The Tangihua Complex rocks similarly display rather variable Sr isotopic ratio (($^{87}Sr/ ^{86}Sr$)i = 0.7027 to 0.7036; Table 3 - Fig. 9) within the same range of variation, and positive and constant ε_{Nd} values ($+7.8 < \varepsilon_{Ndi} < +8.3$). In contrast with Tangihua Volcanics, there is apparently in the Matakaoa Volcanics no occurrence of mafic rocks with high compatible elements contents (Mg, Cr, V), and referred to as "boninite-like" by Whattam et al. (2006).

Both mafic complexes are very similar with respect to the age of enclosed pelagic sediments (Campanian to mid-Eocene), timing of tectonic emplacement, lithology, mineralogy, and geochemistry. The very close similarity suggests that they have a common origin and were once parts of the same slice of Late Cretaceous to Early Eocene "ocean" floor, the bulk of which has been consumed along one of the convergent plate boundaries in the northern New Zealand region in the mid Tertiary. The geochemical characteristics of the Matakaoa Volcanics, and the features of associated sediments and polymetallic mineralisation indicate that they have formed in an extensional back-arc basin, which is similar to the back-arc setting proposed for the Tangihua Complex in the Northland Allochthon (Thompson et al., 1997; Nicholson, 2002a, b).

Comparison of Northland and East Coast allochthons

Stonely (1968) was the first to recognise that the Cretaceous to Tertiary beds of the East coast of the North Island were an allochthon emplaced in a south-westerly direction by gravity sliding onto a structurally simple Cretaceous autochthon and discordantly overlain by upper Tertiary sediments. In this seminal paper he recognised at least 20 slices of coherent sediments, each emplaced before the next (older) slice was slid on top of it and a trend for the oldest, highest thrust slices in the sequence to be the most deformed. While there has been some refinement of Stonely's concept as the thrust sequences have been examined in detail and particularly traced to the north of the Raukumara Peninsula, the basic concepts are now accepted. The East Coast Allochthon is now considered to be composed of 5 groups of thrusts, in which the individual slices are closely related. Many sediments in the thrust sequence have lateral equivalents to the Southwest and represent deposition at greater depths than equivalents in the in-place sequence (Mazengarb and Speden, 2000) and there is some evidence for eastward younging of the deformed sediment / cover basin unconformity (Kenny, 1984). Rait (2000a) estimates that Cretaceous to Oligocene rocks in the East Coast Allochthon have been moved possibly 300 kilometres from their original site of deposition. The Matakaoa Volcanics constitute the sheet at the top and back of the thrust pile and are thus believed to be the oldest slice in the sequence (Mazengarb and Speden, 2000).

The Northland Allochthon extends at least 300 km along the centre and west of the Northland Peninsula (Fig. 2) reaching estimated thicknesses of up to 4000m in central Northland. The sedimentary units in the Northland Allochthon are typically highly deformed compared with the underlying in situ sequence, and melange and broken formation are widespread. At least six thrust slices have been recognised and the Tangihua Volcanics occur in the structurally highest sheet (Isaac et al., 1994). As is the case in the East Coast Allochthon, the higher level thrust slices in the Northland Allochthon are more deformed and show evidence of reimbrication by continued thrusting, particularly on the sub-ophiolite thrust (Rait, 2000b). From north to south in the Northland Allochthon the slices become more disrupted and in its southern part it is composed of small masses as well as dismembered blocks of Tangihua Volcanics and slices of sediment intercalated with Miocene sediments.

The timing and direction of emplacement, and the age of the sediments in the two allochthons are similar (see Hollis and Hanson, 1991). The thrust sequences in the East Coast Allochthon appear to be more coherent than those in the Northland Allochthon. The sediments in the two units are all marine but there are differences in the nature of the sedimentary material in the two allochthons. Allochthonous sediments are in general more pelagic than those of the same age in the autochthon; however, in the East Coast region sediments in the allochthon are sometimes so similar to those in the autochthon that they can be distinguished only on differences in structural style (Mazengarb and Speden, 2000). In Northland, the sediments in the allochthon have clear facies (environment of deposition) differences compared with those in the autochthon. In spite of this and the fact that the East Coast and Northland Allochthons are over 300 km apart, because of their strong similarities they have frequently been correlated and it is assumed that the same regional tectonic event has been responsible for their emplacement. Both allochthons have been emplaced from a north-easterly direction and are displaced about 300 km (Rait, 2000a). The geochemical features presented in this paper confirm and reinforce the assessments of previous authors.

Both the Tangihua Complex and Matakaoa Volcanics contain deformation that was sustained prior to emplacement. In the case of the Tangihua Volcanics there is additional evidence for delamination and disruption, although without substantial displacement, and that they were then remobilised at about 30 Ma (Nicholson &

Black, 2004). There is no evidence of a metamorphosed sole either in the Matakaoa Volcanics or in the Tangihuas; this indicates that no hot, e.g. young lithosphere, was directly involved in the obduction process (see below). We presume that the Matakaoa Volcanics like the Tangihuas have had a complex post-formational but pre-emplacement history that may be related to pre-obduction tectonic accretion.

Hence, the term "ophiolite" which has been sometimes used for the Matakaoa Volcanics (and Tangihua Complex as well) should be avoided because these rocks do not represent obducted parts of a coherent oceanic lithosphere, but rather a mafic melange probably formed by tectonically sliced parts of an upper "oceanic" crust and the associated bathyal sediments. The lack of terrigenous deposits is strong evidence for the melange to have occurred away from any continental source well before the final thrusting over Miocene rocks. All these lithologies may have been scraped off the down going plate, accreted in a fore-arc setting, and finally thrust "en bloc" onto the continental margin during the final closure of the basin.

Age problems

In recent papers (Whattam et al., 2005; 2006, 2008), the correlation of the Northland "Ophiolite" with the Late Cretaceous-Paleogene has been questioned, mainly on the basis of new Ar-Ar ages. Dating of mafic rocks by the Ar-Ar whole rock method provides evidence for consistent Oligocene apparent ages (25-30 Ma) for some parts of the mafic allochthon. In addition, Oligocene U-Pb zircon ages (ca. 30 Ma) have been obtained from one felsic dyke (Whattam et al., 2005) and a gabbro (Whattam et al., 2006). Thus, the bulk of the Northland Complex was reassigned to the Oligocene and obduction was thought to have followed oceanic accretion very closely (Whattam et al., 2008). However, this interpretation is problematical, especially because no large Oligocene basin is known to have existed to the North of New Zealand and also because obduction did not involve hot lithosphere (see above). In addition, Oligocene ages are inconsistent with the available stratigraphic data, as no fossils younger than Early Eocene have been hitherto found within the mafic terranes (cf. section above). It has been pointed out by Nicholson et al. (2007) that some of these new dates have been obtained from basalts that contain much older interpillow sediments already dated by radiolarian fossils. Large volumes of basalt are affected to various degrees by low to medium grade (ocean floor?) metamorphism

(Pirajno, 1980; Black, 1989; Nicholson & Black, 2004) resulting in some elemental mobility and radiogenic argon input, giving unreliable Ar-Ar apparent ages at ca. 300 Ma (Nicholson, 1999). Such older apparent ages are likely due to the massive absorption of hydrous fluids containing radiogenic Ar during water-rock interaction; in contrast, much younger ages (ca. 25-30 Ma) may be related to argon loss during a subsequent thermal event (e.g. intrusion of Oligocene dolerite and/or to the end of hydrothermal circulation) (Nicholson, 2007).

If we consider some of the Oligocene Ar-Ar ages reliable and unaffected by a possible post-eruption reset, the inconsistency between paleontological and radiochronological ages may be solved only if the Late Cretaceous-Paleogene basalt formed the basement through and upon which Oligocene basalts erupted. It is worth noting that the Oligocene gabbro contains reworked Early Cretaceous zircons (Whattam et al., 2006), a feature which is not consistent with the "oceanic" and uncontaminated character of Tangihua volcanics. Zircons would not travel from the subduction zone into supra-subduction melts unless the zircon-bearing slab rocks were melting. But this is not such a common occurrence and it is obviously not the case as adakite-like and other slab-melt rocks are not found in either the Tangihua or in the Matakaoa Volcanics. The Oligocene (30 Ma) "plagiogranite" and gabbro dykes dated by U-Pb zircon dating (Whattam et al., 2005; 2006) may thus be minor fore-arc magmas that have been emplaced through an older basement. This interpretation suggests the existence to the north of the North Island of an Oligocene volcanic arc partly buried below Miocene to Recent volcanic rocks and sediments. This Oligocene volcanic arc, remnants of which had been first identified in offshore dredges (Mortimer et al., 2007), has been recently explored in more detail (Herzer et al., 2009), and it could be coeval with and extend northward into the Three Kings Ridge and farther north into the older Loyalty volcanic-arc.

Regional correlation: Late Cretaceous back-arc basins of the Southwest Pacific

Based upon bulk geochemical similarities, it has been proposed earlier that Matakaoa and Tangihua basalts might be correlated with Hikurangi Plateau rocks (Hayward et al., 1989; Mortimer and Parkinson, 1996); however, this correlation does not account for the critical differences between them as evidenced by modern geochemical data (Mortimer et al., 1998, this study). Hikurangi Plateau basement rocks formed between ca. 120-100 Ma and the seamounts that overlie it between ca. 99-86 Ma (Hoernle et al., 2005). The basement E-MORB display isotopic signatures (($^{87}Sr/^{86}Sr)_i$ = 0.70361- 0.70374; εNd_i = 5.7-6.2) which are consistent with magma generation in a fertile asthenospheric source without any evidence for supra-subduction features (Mortimer and Parkinson, 1996). Thus, the Hikurangi basalts are much older (ca. 120-90 Ma) than the Matakaoa Volcanics (ca. 95-50 Ma), have been generated by contrasting mantle sources (Fig. 8) and owing to their present location on the Pacific Plate, have most probably erupted farther east. Thus the correlation is not supported by our new geochemical data and should be ruled out.

In other places of the Southwest Pacific, the occurrence of Late Cretaceous-Paleocene back-arc basins to the east or north-east of the Norfolk Ridge has been firmly established on geochemical (Eissen et al., 1998; Cluzel et al., 2001), paleontologic (Aitchison et al., 1995; Cluzel et al., 2001), paleomagnetic (Ali and Aitchison, 2000), and geophysical bases (Mauffret et al., 2001; Bernardel et al., 2002). The existence of such fragments is corroborated by the occurrence of very deep (ca. 4,500-5,000 m; i.e. old) oceanic crust forming parts of the South Norfolk Basin (Mauffret et al., 2001). This is evidence for Late Cretaceous "oceanic" basins having existed to the east of the Norfolk Ridge. These basins, that probably extended 500 km to the north and north-east of New Caledonia (Ali and Aitchison, 2000; Schellart et al., 2006), have almost completely disappeared as the result of north-eastward subduction and slab roll-back during the Eocene and Oligocene. This subduction produced the Loyalty, Three Kings (in parts) and possibly Northland Plateau volcanic-arcs.

In New Caledonia, Late Cretaceous to Paleocene mafic oceanic rocks form a 400 km long complex, referred to as the Poya Terrane (Cluzel et al., 1994), underneath the ultramafic ophiolite. The Poya Terrane is a peel-off melange, i.e. a matrix-free juxtaposition of fragments and slivers of the upper oceanic crust, characteristically lacking any terrigenous component, which was formed in the Late Eocene in an intra-oceanic fore-arc setting. It is composed of generally upright km-scale slices of pillowed and massive basalt associated with thin abyssal argillite/radiolarite and rare pelagic limestone. The accreted material originated in a marginal basin located to the east of the Norfolk Ridge and referred to as the South Loyalty Basin (Cluzel et al., 2001). The Poya Terrane rocks are dominantly undepleted MORB (E-MORB), rare BABB and a few younger OIB volcanics that have been interpreted to represent a marginal basin in which magma was generated in conditions similar to that of the North Fiji Basin (see Eissen et al., 1996; Cluzel et al., 2001). In such back-arc basins, the supra-subduction signature is generally weak, and only magmas formed from a metasomatised upper mantle are likely to display BABB (i.e. supra-subduction) features.

Thus, there are significant differences between the Tangihua/Matakaoa back-arc basin that opened to the north of New Zealand and the South Loyalty Basin that formed to the east and northeast of New Caledonia (Nicholson et al., 2000b). The synchronous opening of two dissimilar back-arc basins to the east of the Norfolk Ridge during the Late Cretaceous suggests the existence of a right-lateral transform fault zone that separated the Tangihua/Matakaoa and South Loyalty basins. Following the kinematic model for the opening of the Southeast Gondwana marginal basins (Gaina et al., 1998; Sutherland, 1999; Hall, 2002; Schellart et al., 2006), we suggest that the transform fault extended north-eastward, was inherited from the break-up fracture set (see model below), and allowed a differential opening of the two marginal basins and the overall north-eastward migration of the volcanic arc (Fig. 11). The Northland volcanic-arc/back-arc system was probably limited to the east by another pre-existing transform fault while the northern boundary of the system and its connexions with the Solomon-Papua arc-basins system are still unclear.

South Gondwana break-off: arc- or non arc-related ?

It is generally considered that the end of the South Gondwana active margin activity in New Zealand that occurred at ca. 100-105 Ma (Mortimer, 2004) may be related to the subduction of a spreading ridge (Bradshaw, 1989); and/or the attempted subduction of the Hikurangi oceanic plateau on the Southeast Gondwana active margin (Mortimer and Parkinson, 1996; Mortimer et al., 2006; Davy et al., 2008). Thus, the opening of the Southwest Pacific marginal basins at ca. 90 Ma (Tasman Sea, New Caledonia Basin, etc.) has been interpreted in terms of a Large Igneous Province (Bryan et al., 1997), a feature generally triggered by a mantle plume.

Evidence for Early to mid-Cretaceous (120-110 Ma) marginal rifting is widespread in Southeast Australia (Bryan et al., 1997) and in the South Island of New Zealand (Tulloch and Kimbrough, 1989; Spell et al., 2000; Deckert et al., 2002). Logically, the rift activity predates the marginal basin opening at 90 Ma by some 30 Ma; however, extensive intraplate volcanism and development of Otway, Gippsland and other intra-continental basins was almost synchronous with the end of subduction over a wide area. Intrusion of large amounts of adakitic plutons in the 120-105 Ma interval indicates the melting of an eclogitized mafic source (Muir et al., 1995; Mortimer et al., 1999). Therefore, it may be postulated that the slab rollback that followed the end of subduction triggered a prominent eastward flow of the asthenospheric mantle that heated the base of the lithosphere and generated the adakitic magmas by partial melting of previously underplated mafic rocks. It was also responsible for the large-scale boudinage and extensional break-off of the southeast Gondwana margin (Fig. 12).

In Australia and in New Zealand as well, no post-Early Cretaceous active margin magmatism has hitherto been evidenced and this has been taken as an evidence for a purely extensional tectonic setting. However, the occurrence of 100 Ma old detrital zircons in the volcaniclastic greywackes of “basement” terranes of New Zealand (Cawood et al., 1999), and New Caledonia (Adams and Cluzel, in press; Cluzel, et al. submitted) indicates the persistence of subduction until the upper Early Cretaceous (Albian), at least in the northern part of the system, after a short period of quiescence that may be related to the "collision" of Hikurangi Plateau. In addition, younger Late Cretaceous (ca. 90-80 Ma) high-K calc-alkaline and IAT-like volcanic activity is reported in New Caledonia (Noumea and Diahot regions respectively) (Black, 1995; Picard, 1995), and also in New Zealand (Mount Camel Terrane, Northland and the Three Kings Islands) (Nicholson and Black, 2004). Therefore, we suggest that the eastward push caused by the stretching of the Southeast Gondwana margin reactivated the west-dipping subduction along the eastern end of the system, except in the south where it was blocked by the Hikurangi plateau. Once this subduction was reactivated, the slab roll-back of the old, dense Pacific plate generated two new back-arc basins, the South Loyalty basin to the north, and the Matakaoa/Tangihua basin to the south, after which they evolved independently (Fig. 11).

A model for the obduction of Northland and East Coast Allochthons.

For a long time it has been commonly accepted that the Northland Allochthon and its East Coast correlative were obducted onto the North Island continental margin as a result of south-dipping subduction (Ballance and Spörli, 1979; Parrot and Dugas, 1980; Brothers and Delaloye, 1982; Spörli, 1989; Malpas et al., 1992; Nicholson et al., 2000a; Herzer et al., 2000; Whattam et al., 2005); however, this view is now questioned and an increasing number of authors consider the possibility of north or north-east dipping subduction having occurred prior to obduction. (Cluzel et al., 1999; Bernardel et al., 2002; Sdrolias et al., 2003; Crawford et al., 2003; Bradshaw, 2004; Schellart et al., 2005; Whattam et al., 2006, 2008).

The model of south dipping subduction suggests delamination and accretion of slivers of oceanic upper crust onto the former passive margin (flaking). However, it is difficult to reconcile this model, that would have resulted in a relatively narrow, fan-shaped, mainly north-verging accretion complex, with the shortening that results from computing the throws of all parts of the allochthon (Rait, 2000a) and paleomagnetic data (Cassidy, 1993; Whattam et al., 2005), all of which indicate a southward relative motion of ca. 300 km. Advocating southward gravitational sliding apparently solves this inconsistency but requires a large pre-existing slope which is not substantiated on paleogeographic grounds.

Sea-floor spreading data for the Late Eocene – Early Miocene Pacific – Australia plate motion indicates that the Pacific - Australian plate boundary motion was slightly oblique, with the Pacific plate moving south-westward relative to the Australian plate at c. 25-30mm/year. It has been suggested that it was this movement that tipped ocean floor material onto the autochthonous sediments (Rait, 2000b). However, this model implies that the Northland basin was at that time part of the Pacific plate, but this was not the case because the Vitiaz-Fiji-Tonga subduction system was already active.

The obduction of the fore-arc region of a north- or northeast-dipping subduction zone within the Australian plate can account for all the features of the Northland and East Coast allochthons and allow integration in a coherent regional model. The existence of an Eocene to Oligocene north- or northeast-dipping subduction zone to the east of the Norfolk ridge is now firmly established by the occurrence of: i) Late Eocene subduction-related accretion, high-pressure metamorphism and obduction in New Caledonia (Aitchison et al., 1995a; Cluzel et al., 1999; Cluzel et al., 2001); ii) Eocene andesite drilled on the Bougainville seamount (Andrews et al., 1975); and, iii) mid- to Late Eocene andesitic volcanoclastic turbidites that have been drilled in the North-Loyalty Basin, at the DSDP 286 site (Andrews et al., 1975). Convergence was still active in the Late Oligocene and generated the 27-24 Ma post-obduction granodiorites of New Caledonia (Cluzel et al., 2005; Paquette and Cluzel, 2007). Recently, the discovery of ophiolite remnants, Early Oligocene boninite (Bernardel et al., 2002) and 31 Ma old blueschist on the western edge of the Three Kings Ridge (Meffre et al., 2006) provide further evidence of a subduction/obduction system that extended from New Caledonia to the Norfolk basin. We suggest that this subduction zone extended southward and that mafic allochthons of Northland and East Coast represent the obducted fore-arc of the now buried Oligocene Northland Plateau arc, and are back-arc lithosphere (Late Cretaceous-Eocene) in a fore-arc position (Oligocene) (Fig 12). According to our model, some of the IAT pillow lavas (if any) and the Oligocene intrusive rocks that crosscut Late Cretaceous-Eocene basalts may be evidence of the Oligocene volcanic-arc/fore-arc activity. The pre-obduction melange features observed in the East Coast Allochthon thus represent remnants of a peel-off melange similar to the Poya terrane of New Caledonia that developed in an early stage of intra-oceanic convergence away from any terrigenous source. The sedimentary components of the allochthon are docked in an in-sequence order and mainly display southward verging tectonic features that are consistent with the progressive duplexing and underplating of sediments that originally accumulated on a northward deepening passive margin. The topography that resulted from the flexural bend due to overburden on one hand, and tectonic imbrication on the other, allowed the final gravitational sliding of the southernmost parts of the allochthon as observed in Northland.

Conclusion

The mafic allochthonous terranes of northern New Zealand (Matakaoa Complex and Tangihua Volcanics) have most probably been generated in a single Late Cretaceous-Early Eocene back-arc basin. Correlation of the Matakaoa and

Tangihua volcanic rocks with those of the giant Cretaceous Hikurangi-Manihiki-Ontong Java Plateau (Taylor, 2005), which is significantly older and erupted in a quite different geodynamic setting, can be ruled out. It is proposed that the Hikurangi Plateau, the southernmost fragment of the giant Early Cretaceous plateau, choked the subduction zone and was responsible for the fan -shaped opening of the easternmost Late Cretaceous marginal basins of the Southwest Pacific. A direct connection between the back-arc basin in which the Matakaoa and Tangihua Volcanics were generated, and the synchronous South Loyalty back-arc basin (New Caledonia) is not possible, as they display arguably different geochemical features and transform faults are likely to have operated during their opening. Late Paleocene/Early Eocene subduction reversal was responsible for westward and thereafter south-westward arc/trench migration that finally resulted in a diachronous obduction that propagated southwards. In northern New Zealand, the Late Cretaceous-Early Eocene mafic rocks are crosscut and possibly overlain by some younger, Early Oligocene volcanic rocks which represent the arc/fore-arc activity that closely preceded obduction.

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Figure captions

Figure 1: Sketch map of the Southwest Pacific (oceanic crust in grey, continental crust in white, volcanic-arc crust dotted). B: Bougainville Seamount.

Figure 2: Geologic sketch map of North Island (New Zealand) to show the location of Northland and East Coast allochthons (dashed) with their Late Cretaceous-Early Eocene oceanic crust components (in black) (adapted from Davey et al., 1997). VMFZ: Veining-Meinesz fracture zone, TVZ: Taupo Volcanic Zone.

Figure 3: Geologic map of the East Coast Allochthon in the northern Raukumara peninsula (simplified after Mazengarb & Speden, 2000), with sample location (grid numbers refer to the 1:50,000 map of New Zealand Y 14 sheet), and local names cited in the text. For map location, see Fig. 2. Insert shows the location of Matakaoa Volcanics within the East Coast Allochthon.

Figure 4: Zr/TiO_2 vs. Nb/Y classification diagram for altered or metamorphic rocks of Winchester and Floyd (1977) to show a limited range of variation of Zr/TiO_2 which represents differenciation; in contrast, a wide range of Nb/Y values is related to contrasting sources and reflects a variable Nb depletion.

Figure 5: Th/Yb vs. Ta/Yb discrimination diagram of Pearce (1983) to show the range of variation of Ta/Yb which allows the discrimination of the four rock types discussed in the text.

Figure 6: Chondrite-normalised REE diagram (a) and N-MORB-normalised expanded REE-trace elements spiderdiagram (b) of Matakaoa volcanic rocks (East Coast Allochthon) – Normalization values are from Pearce (1980) and Sun and McDonough (1989).

Figure 7: Ploted against the (Nb/La)n ratio which represents the increasing subduction influence in Matakaoa Volcanics from MORB-like to IAT-like end-members, Sr and Pb contents do not show any correlation; a feature which suggest only a minor or negligible influence of subduction-derived or continental crust material.

Figure 8: Sr and Nd isotopic ratios of Tangihua and Matakaoa volcanic rocks (Table 3) after Ben Othman et al. (1989). A shift towards higher $^{87}Sr/^{86}Sr$ ratios for constant εNd_i values (especially prominent for the "teshenite") is a common feature of volcanic rocks mildly altered by "hydrothermal" processes (e.g. sea water-rock interaction). A plot of three leached samples of Hikurangi Plateau basalts with distinctively lower εNd_i (Mortimer and Parkinson, 1996) is shown for comparison.

Figure 9 : Chondrite-normalised REE diagram (a) and MORB-normalised expanded REE-trace elements spiderdiagram (b) of Tangihua volcanic rocks (Northland Allochthon) – same references as Fig 5. Data from Nicholson et al (2000a).

Figure 10 : Th/Yb vs. Ta/Yb discrimination diagram of Pearce (1983) to compare the range of variation of Mataoa Volcanics and Tangihuas Complex basalts that both plot within the same restricted field and the fields of Lau, Mariana and East Scotia back-arc basin basalts (data from Langmuir et al., 2006). New Zealand's allochthonous basalts appear to have been generated in conditions intermediate between the juvenile Lau Basin and the more mature Mariana and East Scotia basins.

Figure 11: A tentative reconstruction of the evolution of south-eastern Gondwana margin in the Late Early Cretaceous (ca. 105 Ma, 10a) (modified from Gaina, et al., 1998, Sutherland, 1999, and Hall, 2002), and Paleocene (ca. 70 Ma, 10b) (modified from Cluzel et al., 1999; this study), to show the marginal basins in which the mafic allochthons of New Caledonia and New Zealand have been generated. Plate boundaries are only indicative due to syn-rift stretching and subsequent Tertiary tectonics. NC: New Caledonia, LHR: Lord Howe rise, MBL: Mary Byrd Land, NLB: North Loyalty Basin, SFB: South Fiji Basin, Camp: Campbell Plateau, Chall: Challenger Plateau, Chath: Chatham Plateau, Hiku: Hikurangi Plateau.

Figure 12 : A model for Late Cretaceous to Miocene geodynamic evolution of the Southwest Pacific (modified from Cluzel et al., 1999, no scale). 12a: Early Cretaceous (c. 105 Ma) end of Phoenix/Pacific plate subduction, marginal accretion and Median Batholith activity; 12b: Early Late Cretaceous (c. 90 Ma) slab break-off and incipient boudinage of the lithosphere (note that section 11a is located at a more southerly latitude as 11b); 12c: Campanian-Paleocene (80-65 Ma) Gondwana marginal rifting, subduction reactivation, oceanward arc migration and marginal basin opening; 12d: Eocene-Oligocene (52-30 Ma) subduction flip initiated at New Caledonia's latitude and propagating southward, formation of an Oligocene island arc; 12e: Early Miocene (ca. 22-20 Ma) attempted subduction of the North Island margin and obduction of Northland and East Coast Allochthons. Boxes legend: 1 oceanic crust; 2 continental crust, 3 lithospheric mantle, 4 asthenosphere.

Annex I: A series of binary diagrams to show the variation of selected major (in wt%), trace elements (in ppm) and elemental ratios versus MgO content of Matakaoa Volcanics which is known to represent the differenciation process. Note the prominent variation of mobile elements (K_2O), the poor correlation of SiO2 and MgO; and in contrast, the relatively good fit of the four rock types defined in this paper with the contents of selected "immobile" trace elements (Ti, REE), and some elemental ratios.

Table 1: location, geologic setting and chemical affinity of the analysed samples of Matakaoa Volcanics.

Sample n°	rock name	setting	Affinity	Location	NZMS 260 1 : 50,000 map / grid reference
PMB32043	basalt	flow	MORB	Potikirua Pt	Y14 / 598935
PMB32046	basalt	flow	IAT	Runaway E	Y14 / 530933
MK-34	doleritic basalt	flow	IAT	Runaway E	Y14 / 522935
MK-38	doleritic basalt	flow	IAT	Runaway E	Y14 / 525933
MK-33	dolerite	dyke	IAT	Runaway E	Y14 / 523934
PMB32008	dolerite	dyke	IAT	Runaway E	Y14 / 504950
PMB32005	basalt	flow	TB	Runaway E	Y14 / 508946
PMB32111	basalt	pillow	TB	Runaway E	Y14 / 508946
PMB32048	dolerite	dyke	BABB	Runaway E	Y14 / 505947
MK-36	doleritic basalt	flow	BABB	Runaway E	Y14 / 517937
MK-37	basalt	flow	BAB	Runaway E	Y14 / 520936
MK-35	basalt	pillow	MORB	Runaway E	Y14 / 514940
MK-30	basalt	pillow	MORB	Runaway W	Y14 / 504920
MK-29	basalt	pillow	MORB	Runaway W	Y14 / 505918
MK-32	basalt	pillow	MORB	Runaway W	Y14 / 506917
PMB15789	variolitic basalt	breccia	MORB	Midway Pt	Z14 / 709933
PMB15831	basalt	dyke	IAT	Midway Pt	Z14 / 710930
MK-21	teschenite	sill	MORB	Lottin Pt	Y14 / 666931
MK-23	teschenite	sill	BAB	Lottin Pt	Y14 / 665925
MK-24	basalt	pillow	IAT	Lottin Pt	Y14 / 649926
MK-14	dolerite	dyke	IAT	Lottin Pt	Y14 / 662925
MK-16	basalt	pillow	IAT	Lottin Pt	Y14 / 662925
MK-27	dolerite	dyke	IAT	Lottin Pt	Y14 / 633278
MK-45	gabbro	dyke	MORB	Lottin Pt	Y14 / 645930
PMB15856	basalt	glass	IAT	Lottin Pt E	Y14 / 692938
MK- 2	dolerite	breccia	IAT	Matakaoa pt	Z14 / 782909
MK- 3	andesite	flow	IAT	Matakaoa pt	Z14 / 764917
MK- 4	basalt	hyaloclastite	IAT	Matakaoa pt	Z14 / 767917
MK- 8	dolerite	volc. breccia	IAT	Matakaoa pt	Z14 / 773916
MK-13	basalt	hyaloclastite	IAT	Matakaoa pt	Z14 / 784915
MK- 7	andesitic basalt	clast	IAT	Matakaoa pt	Z14 / 773916
MK-10	andesitic basalt	flow	IAT	Matakaoa pt	Z14 / 779916
MK-12	basalt	breccia	IAT	Matakaoa pt	Z14 / 784915
MK- 1	basalt	flow	BABB	Pukeamaru E	Z14 / 782874
MK-48	basalt	clast	IAT	Pukeamaru E	Z14 / 796864
MK-40	basalt	flow	BABB	Pukeamaru N	Y14 / 650853
MK-46	basalt	volc. breccia	MORB	Pukeamaru	Z14 / 803869
MK-41	dolerite	flow	BABB	Pukeamaru S	Z14 / 760803
MK-42	basalt	pillow	MORB	Pukeamaru S	Z14 / 759802

Table 2: Major and trace element compositions of Matakaoa volcanic rocks (major elements in wt.%, trace elements and REE in ppm)

Sample n°	PMB32043	MK-46	MK-42	MK-35	MK-30	MK-29	MK-32	MK-21	PMB15789	MK- 1	MK-40	PMB32048	MK-36
Name	basalt	basaltic breccia	pillow basalt	pillow basalt	pillow basalt	pillow basalt	pillow basalt	tesche-nite sill	variolit. basalt	basalt	basalt	dolerite	dolerite. basalt
Affinity	MORB	MORB	MORB	MORB	MORB	MORB	MORB	MORB	MORB	BAB	BAB	BAB	BAB
Location	Potikirua Pt	Pukeamaru	Pukeamaru S	Runaway E	Runaway W	Runaway W	Runaway W	Lottin Pt	Midway Pt	Pukeamaru E	Pukeamaru N	Runaway E	Runaway E
SiO2	49.52	47.76	50.46	48.92	47.73	49.22	50.62	50.67	48.55	48.97	48.89	48.43	50.20
TiO2	2.14	2.25	1.75	1.75	2.04	2.52	2.73	1.94	2.39	1.38	1.79	1.45	1.35
Al2O3	14.01	14.63	14.26	14.59	13.87	13.57	13.78	15.36	13.57	14.89	13.99	12.78	15.46
Fe2O3$_T$	11.96	12.45	11.92	11.22	12.40	12.30	11.16	12.05	13.67	10.72	11.83	10.74	10.54
MnO	0.22	0.20	0.20	0.17	0.21	0.28	0.18	0.23	0.22	0.19	0.18	0.17	0.17
MgO	6.08	6.60	5.83	7.55	6.95	5.77	5.76	4.98	6.26	7.14	6.26	9.06	6.97
CaO	9.56	10.78	10.25	10.13	9.08	10.90	9.06	7.54	9.92	9.26	8.36	11.29	11.65
Na2O	3.58	3.07	2.76	3.61	3.93	3.05	4.02	5.10	2.93	3.92	4.70	2.96	2.23
K2O	0.31	0.30	0.19	0.15	0.36	0.19	0.76	0.42	0.31	0.62	0.11	0.17	0.13
P2O5	0.27	0.24	0.17	0.21	0.19	0.24	0.26	0.22	0.26	0.13	0.16	0.13	0.14
Loi+	1.18	1.10	2.14	1.78	2.91	1.40	1.14	1.19	0.82	2.01	2.38	2.23	1.11
H2O-	0.86	0.77	0.14	0.08	0.40	0.49	0.47	0.28	0.46	0.72	1.17	0.34	0.05
Total	99.69	100.14	100.06	100.18	100.05	99.93	99.93	99.97	99.34	99.95	99.83	99.76	100.00
Co	44.6	41.6	nd	41.2	42.7	64.8	42.0	31.8	61.2	36.6	39.0	53.1	40.1
Cr	230	218	102	318	268	253	158	55	199	318	172	702	290
Ni	61.7	65.4	42.9	108.4	75.6	77.3	67.5	33.2	84.5	72.2	51.5	134.7	81.1
Ga	19.4	20.1	20.9	18.8	21.0	20.6	21.3	21.5	20.5	15.9	17.3	14.7	17.3
Sc	38.2	41.0	38.0	37.2	41.5	46.1	48.9	41.8	44.7	43.6	43.1	56.4	35.1
V	362	404	364	309	413	441	430	352	397	316	365	322	291
Ba	29.1	13.7	30.8	17.0	54.4	21.9	61.4	353.3	20.1	33.4	571.1	23.9	16.5
Rb	3.70	1.98	2.59	1.80	1.29	3.05	15.25	5.98	3.05	3.88	1.58	2.15	2.21
Sr	155	170	127	120	110	119	127	173	125	253	166	181	128
Y	57.9	54.2	42.2	42.8	43.7	57.6	56.4	48.6	56.8	31.7	41.5	37.6	32.3
Zr	199	184	129	143	135	177	187	119	198	89	120	73	94
Nb	5.50	4.54	3.03	4.12	3.90	4.44	4.97	4.09	4.96	1.67	1.86	2.72	2.68
Cs	0.03	0.02	nd	0.16	0.08	0.05	0.19	0.12	0.05	0.15	0.82	0.23	0.07
Hf	4.83	4.43	nd	3.73	3.50	4.49	4.98	3.30	5.03	2.40	3.14	2.21	2.49
Ta	0.360	0.308	nd	0.281	0.249	0.303	0.343	0.259	0.400	0.151	0.132	0.160	0.177
Pb	1.43	0.47	2.37	0.39	0.53	0.87	0.55	0.61	0.89	0.89	0.24	0.64	0.39
Th	0.390	0.324	0.000	0.306	0.230	0.278	0.324	0.241	0.386	0.182	0.159	0.126	0.280
U	0.175	0.187	2.280	0.151	0.102	0.107	0.293	0.222	0.152	0.122	0.116	0.139	0.104
La	7.53	6.18	1.55	5.79	4.31	5.33	5.47	6.05	7.25	3.06	3.58	4.10	3.96
Ce	22.45	18.78	14.16	17.17	13.45	17.38	19.73	18.12	20.89	9.53	11.77	12.88	11.70
Pr	3.72	3.14	nd	2.84	2.35	2.99	3.35	3.05	3.58	1.69	2.10	2.04	1.97
Nd	18.49	16.67	nd	14.42	12.64	16.29	18.04	15.85	18.83	9.22	11.69	10.87	10.14
Sm	6.22	5.59	nd	4.65	4.45	5.67	6.27	5.24	5.81	3.17	4.13	3.96	3.35
Eu	1.95	1.80	nd	1.65	1.53	1.88	2.17	1.75	1.96	1.15	1.45	1.25	1.22
Gd	7.66	6.93	nd	5.84	5.90	7.45	8.19	6.83	8.13	4.12	5.81	5.00	4.28
Tb	1.366	1.290	nd	1.071	1.059	1.409	1.481	1.197	1.442	0.780	1.005	0.884	0.801
Dy	9.50	8.56	nd	6.81	7.08	9.17	9.63	7.56	8.74	5.09	6.61	5.65	5.18
Ho	1.97	1.88	nd	1.49	1.55	2.03	2.08	1.66	1.89	1.15	1.50	1.24	1.16
Er	5.85	5.44	nd	4.28	4.54	5.89	5.81	4.75	5.71	3.28	4.30	3.68	3.31
Tm	3.40	nd	nd	nd	nd	nd	nd	nd	3.55	nd	nd	2.65	nd
Yb	5.38	4.87	nd	3.91	4.25	5.28	5.38	4.37	5.37	3.00	3.88	3.29	3.08
Lu	0.830	0.748	nd	0.588	0.662	0.779	0.799	0.649	0.815	0.462	0.593	0.515	0.479

Sample	MK-23	MK-24	MK-14	MK-16	MK-27	MK- 2	MK-13	MK- 7	MK-10	MK-12	PMB15831	MK-48	PMB32046
Name	Tesche-nite sill	pillow basalt	dolerite	pillow basalt	dolerite	dolerite breccia	vitric nodule	andesitic clast	andesitic basalt	basaltic breccia	basaltic dyke	basaltic clast	basalt
Affinity	BAB	IAT	IAT	IAT	IAT	IAT	IAT	IAT	IAT	IAT	IAT	IAT	IAT
Location	Lottin Pt	Lottin Pt	Lottin Pt	Lottin Pt	Lottin Pt	Matakaoa pt	Matakaoa pt	Matakaoa pt	Matakaoa pt	Matakaoa pt	Midway Pt	Pukeamaru E	Runaway E
SiO2	49.94	50.62	50.89	52.64	49.37	52.23	49.90	55.79	56.80	51.61	48.28	52.85	51.53
TiO2	1.54	1.46	1.12	1.59	1.31	1.13	1.33	1.59	1.26	1.36	1.47	1.12	1.51
Al2O3	14.67	15.02	15.41	14.40	18.58	15.53	15.56	14.66	14.81	15.44	14.98	14.84	14.84
$Fe2O3_T$	10.16	10.62	9.64	11.50	9.27	9.08	9.91	10.43	8.31	9.99	11.31	10.99	11.64
MnO	0.19	0.15	0.17	0.17	0.15	0.15	0.16	0.15	0.12	0.17	0.18	0.13	0.19
MgO	6.37	5.46	7.08	4.75	4.81	6.42	6.07	4.06	4.52	6.23	6.49	6.47	5.85
CaO	11.30	7.51	9.64	8.21	10.23	9.63	11.29	8.79	9.47	10.90	10.57	7.28	9.44
Na2O	3.50	5.29	3.69	3.70	4.00	3.59	2.74	3.35	2.91	2.79	3.03	3.38	2.69
K2O	0.19	0.35	0.34	0.25	0.15	0.87	0.38	0.53	0.21	0.34	0.20	0.42	0.37
P2O5	0.14	0.14	0.10	0.15	0.12	0.13	0.13	0.16	0.12	0.14	0.14	0.12	0.14
Loi+	1.90	1.89	1.04	1.22	1.90	0.55	0.93	0.34	0.22	0.43	0.75	2.06	1.51
H2O-	0.29	1.49	0.80	1.38	0.26	0.78	1.70	0.41	1.42	0.77	2.16	0.97	0.26
Total	100.19	100.00	99.93	99.96	100.14	100.09	100.09	100.24	100.18	100.16	99.55	100.64	99.98
Co	36.7	30.6	37.8	33.3	35.2	37.2	42.4	31.1	35.4	46.9	51.1	29.3	39.0
Cr	201	125	270	93	133	266	334	142	190	287	129	228	154
Ni	65.3	31.6	87.0	30.8	37.0	73.7	99.6	25.0	47.7	63.0	64.3	68.5	35.2
Ga	18.2	19.0	16.6	19.7	19.1	19.3	17.2	20.3	17.4	17.4	19.1	17.6	18.1
Sc	44.4	30.5	37.4	36.6	29.5	30.1	38.1	31.7	38.4	39.1	39.2	31.8	37.9
V	323	356	300	377	267	275	313	370	307	320	343	297	356
Ba	26.9	23.9	15.5	12.4	161.9	45.0	21.2	27.4	20.2	23.6	9.6	32.1	77.6
Rb	2.33	7.62	3.93	2.19	2.45	7.86	4.84	14.77	1.43	5.96	2.16	8.10	5.45
Sr	162	102	205	139	169	149	152	154	131	155	140	125	131
Y	37.9	34.8	27.7	38.7	37.1	40.6	32.2	40.5	31.7	40.4	35.5	28.2	34.0
Zr	111	107	75	116	106	138	88	124	93	116	100	84	97
Nb	2.73	1.76	1.22	1.66	1.83	1.75	1.32	1.81	1.71	2.22	1.80	1.34	1.86
Cs	0.06	0.28	0.05	0.02	0.15	0.05	0.08	0.47	0.04	0.08	0.01	0.33	0.26
Hf	2.82	2.68	1.99	3.10	2.89	3.21	2.27	2.85	2.42	2.54	2.81	2.26	2.62
Ta	0.180	0.110	0.081	0.113	0.129	0.106	0.090	0.111	0.117	0.121	0.146	0.091	0.127
Pb	0.33	0.40	0.53	0.74	0.22	0.51	0.60	0.58	0.90	0.86	0.80	0.37	0.75
Th	0.195	0.255	0.185	0.296	0.193	0.295	0.210	0.308	0.251	0.242	0.227	0.247	0.215
U	0.081	0.106	0.197	0.184	0.091	0.236	0.701	0.105	0.100	0.180	0.097	0.109	0.091
La	4.29	3.85	2.82	4.02	3.48	4.51	3.23	4.38	3.45	4.06	3.75	2.89	3.23
Ce	12.93	11.53	8.57	12.61	10.96	13.98	10.09	13.61	10.58	12.25	11.31	8.82	9.77
Pr	2.17	1.97	1.48	2.15	1.94	2.35	1.76	2.26	1.78	2.07	1.96	1.50	1.72
Nd	11.34	10.29	8.00	11.52	10.61	12.05	9.52	12.08	9.51	10.88	10.54	8.13	9.32
Sm	3.84	3.55	2.71	3.96	3.68	4.14	3.21	3.99	3.37	3.68	3.56	2.79	3.26
Eu	1.42	1.27	1.01	1.38	1.32	1.38	1.20	1.39	1.11	1.26	1.28	1.02	1.16
Gd	4.92	4.53	3.64	5.01	4.86	5.04	4.22	5.11	4.21	4.60	4.95	3.76	4.51
Tb	0.926	0.834	0.659	0.924	0.897	0.919	0.772	0.952	0.802	0.897	0.898	0.683	0.798
Dy	6.00	5.30	4.26	5.98	5.94	5.94	5.00	5.87	5.00	5.46	5.69	4.49	5.22
Ho	1.29	1.16	0.94	1.32	1.34	1.32	1.10	1.30	1.15	1.21	1.20	1.01	1.14
Er	3.72	3.37	2.71	3.84	3.91	3.83	3.25	3.92	3.29	3.57	3.61	2.94	3.43
Tm	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	2.68	nd	3.29
Yb	3.47	3.25	2.54	3.67	3.53	3.62	2.95	3.65	3.02	3.37	3.47	2.74	3.25
Lu	0.514	0.489	0.381	0.556	0.553	0.545	0.442	0.561	0.463	0.512	0.535	0.404	0.482

Sample	MK-34	MK-38	MK-33	PMB32008	PMB32005	PMB32111	MK-37	PMB15856	MK-45	MK-3	MK-4	MK-8	MK-41
Name	doleritic basalt	doleritic basalt	dolerite	dolerite	basalt	pillow basalt	basalt	Basalt glass	dolerite	andesite	basalt	dolerite	doleritic basalt
Affinity	IAT	IAT	IAT	IAT	TB	TB	BAB	IAT	MORB	IAT	IAT	IAT	BAB
Location	Runaway E	Runaway E	Runaway E	Runaway E	Runaway E	Runaway E	Runaway E	Lottin Pt	Lottin Pt	Matakaoa Pt	Matakaoa Pt	Matakaoa Pt	Pukeamaru S
SiO2	51.16	51.90	52.03	50.72	53.31	48.43	50.18	48.61	49.45	60.26	50.17	56.28	48.59
TiO2	1.76	1.05	1.30	1.27	1.37	0.89	1.51	1.18	1.66	1.42	1.52	1.76	1.59
Al2O3	14.65	15.13	14.77	15.13	18.11	22.82	15.19	14.71	14.45	13.01	14.43	15.03	14.66
Fe2O3$_T$	12.65	10.95	11.44	11.27	7.58	6.72	11.36	10.13	12.08	8.46	11.75	9.75	10.84
MnO	0.20	0.18	0.19	0.18	0.09	0.11	0.17	0.15	0.22	0.12	0.18	0.17	0.18
MgO	5.58	6.48	6.09	6.08	1.67	2.51	6.55	5.85	5.96	3.31	5.14	3.73	6.22
CaO	9.80	10.20	9.88	9.66	9.71	8.66	10.84	8.89	8.25	7.80	9.43	8.53	8.06
Na2O	3.08	2.80	3.00	3.24	2.67	4.54	2.59	1.80	4.40	2.99	2.90	3.65	4.61
K2O	0.09	0.17	0.18	0.17	0.74	1.51	0.16	0.19	0.17	0.18	0.43	0.41	0.60
P2O5	0.14	0.08	0.09	0.10	0.34	0.12	0.17	0.11	0.14	0.13	0.14	0.19	0.16
Loi+	0.99	1.06	1.08	1.43	3.68	1.81	1.35	4.57	2.87	0.73	2.75	0.40	1.75
H2O-	0.09	0.06	0.13	0.39	0.21	0.35	0.08	2.89	0.55	1.72	1.01	0.13	2.68
Total	100.19	100.06	100.18	99.66	99.49	98.47	100.14	99.08	100.22	100.16	99.85	100.02	99.94
Co	37.1	36.3	38.8	34.5	30.8	38.3	36.9	42.9	nd	37.1	34.6	25.3	36.2
Cr	151	146	137	179	134	253	241	215	129	125	166	75	223
Ni	39.5	42.1	40.8	43.1	21.5	56.8	69.5	63	44.5	26.8	39.2	16.9	55
Ga	20.6	16.8	17.6	17.9	20.6	17.0	18.2	16.00	19.2	17.3	18.7	21.3	18.13
Sc	38.9	41.3	43.0	44.2	18.8	22.1	35.7	42	41.4	29.9	34.73	31.9	36.0
V	380	313	346	333	182	86	324	330	362	349	352	435	333
Ba	21.7	32.0	31.9	51.4	133.1	60.9	28.1	32.2	183	24.7	32.3	30.3	72.1
Rb	0.86	2.49	2.69	2.18	13.47	27.88	2.33	2.72	2.38	1.62	3.50	17.0	4.72
Sr	123	104	118	156	422	331	141	114	176	141	134	149	126
Y	38.1	25.4	31.8	30.9	55.4	32.4	35.6	30.16	38.3	33.20	37.52	43.48	37.2
Zr	95	62	77	79	139	64	115	83.7	114	106	113	134	115
Nb	1.43	0.79	0.88	0.97	19.36	4.57	2.497	1.30	2.77	1.500	1.604	1.718	2.29
Cs	0.09	0.14	0.14	0.06	0.25	0.96	0.100	0.09	nd	0.032	0.052	0.510	0.29
Hf	2.71	1.76	2.26	2.21	2.38	1.53	2.689	2.35	nd	2.689	2.866	3.395	2.82
Ta	0.103	0.051	0.064	0.067	1.032	0.238	0.170	0.44	nd	0.091	0.108	0.122	0.15
Pb	0.55	0.08	0.31	1.10	3.36	0.60	0.302	25.8	2.17	0.535	0.757	0.446	0.34
Th	0.175	0.136	0.158	0.180	1.350	0.205	0.279	0.23	nd	0.233	0.280	0.364	0.21
U	0.072	0.061	0.060	0.104	0.633	0.325	0.83	0.16	1.15	1.96	2.05	1.53	0.09
La	3.17	1.90	2.15	2.52	34.33	10.06	4.389	2.98	0.74	3.833	3.967	4.961	3.90
Ce	10.33	6.13	7.32	8.49	71.99	9.88	12.72	9.30	10.93	11.73	12.28	14.93	12.2
Pr	1.86	1.11	1.36	1.48	9.16	2.70	2.095	1.57	nd	2.01	2.10	2.53	2.11
Nd	10.07	6.19	7.65	8.30	36.67	12.33	11.12	8.56	nd	10.43	11.19	13.43	10.86
Sm	3.70	2.34	2.82	3.02	8.12	3.19	3.70	3.00	nd	3.60	3.73	4.35	3.78
Eu	1.34	0.82	1.09	1.11	2.32	1.26	1.25	1.08	nd	1.25	1.32	1.54	1.31
Gd	4.76	3.23	3.93	4.09	8.55	4.14	4.83	4.03	nd	4.54	4.88	5.64	4.75
Tb	0.919	0.582	0.735	0.747	1.43	0.64	0.86	0.75	nd	0.82	0.89	1.05	0.88
Dy	6.17	3.97	5.03	4.81	8.68	4.07	5.71	4.71	nd	5.30	5.92	6.74	5.65
Ho	1.33	0.92	1.10	1.06	1.78	0.91	1.26	1.05	nd	1.16	1.29	1.49	1.24
Er	3.90	2.73	3.24	3.23	5.01	2.69	3.60	3.22	nd	3.43	3.85	4.30	3.62
Tm	nd	nd	nd	2.65	2.97	2.89	nd	2.62	nd	nd	nd	nd	nd
Yb	3.60	2.54	3.09	3.02	4.13	2.42	3.33	3.01	nd	3.21	3.60	4.04	3.43
Lu	0.546	0.388	0.475	0.456	0.617	0.364	0.501	0.45	nd	0.488	0.544	0.595	0.52

Table 3: Sr and Nd isotopic compositions of Matakaoa (East Coast) and Tangihua (Northland) mafic rocks. All the isotopic ratios are back-calculated at 80Ma which is the average fossil age of Matakaoa Volcanics; using a younger age does not significantly change the results.

Sample n°	MK- 4	MK-12	MK-16	MK-38	MK-37	MK-21	MK-35	49211	49164	49183	49186	47648	47662
Rock type	Basalt	Basalt	Pillow basalt	Basalt	Basalt	Teschenite	Pillow basalt	Basalt	Glass	Basalt	Basalt	Pillow basalt	Pillow basalt
Geochemical type	IAT	IAT	IAT	IAT	BAB	MORB	MORB	IAT	IAT	BAB	BAB	BAB	BAB
Terrane	Matakaoa	Matakaoa	Matakaoa	Matakaoa	Matakaoa	Matakaoa	Matakaoa	Tangihua	Tangihua	Tangihua	Tangihua	Tangihua	Tangihua
Assumed age (Ma)	80	80	80	80	80	80	80	80	80	80	80	80	80
Sm (ppm)	3.73	3.68	3.96	2.34	3.67	5.24	4.65	2.32	4.09	3.08	3.55	4.69	4.39
Nd (ppm)	11.2	10.9	11.5	6.18	11.1	15.8	14.4	6.19	11.5	9.13	11.0	14.8	13.9
Rb (ppm)	3.50	5.96	2.19	2.49	2.33	5.98	1.80	0.67	2.51	3.63	2.18	2.13	1.95
Sr (ppm)	134	155	138	104	141	172	120	120	86.4	143	206	130	105
$(^{143}Nd/^{144}Nd)m$	0.51300	0.51306	0.51305	0.51304	0.51304	0.51306	0.51305	0.51306	0.51305	0.51306	0.51306	0.51306	0.51304
$(^{143}Nd/^{144}Nd)i$	0.51290	0.51295	0.51294	0.51292	0.51293	0.51295	0.51294	0.51293	0.51293	0.51295	0.51295	0.51296	0.51294
εNdi	**7.1**	**8.1**	**7.8**	**7.5**	**7.8**	**8.1**	**8.0**	**7.8**	**7.8**	**8.1**	**8.2**	**8.3**	**7.9**
$(^{87}Sr/^{86}Sr)m$	0.70298	0.70222	0.70304	0.70284	0.70284	0.70452	0.70280	0.70361	0.70299	0.70320	0.70349	0.70295	0.70268
$(^{87}Sr/^{86}Sr)i$	0.70290	0.70210	0.70299	0.70277	0.70279	0.70441	0.70276	0.70359	0.70289	0.70311	0.70345	0.70290	0.70262

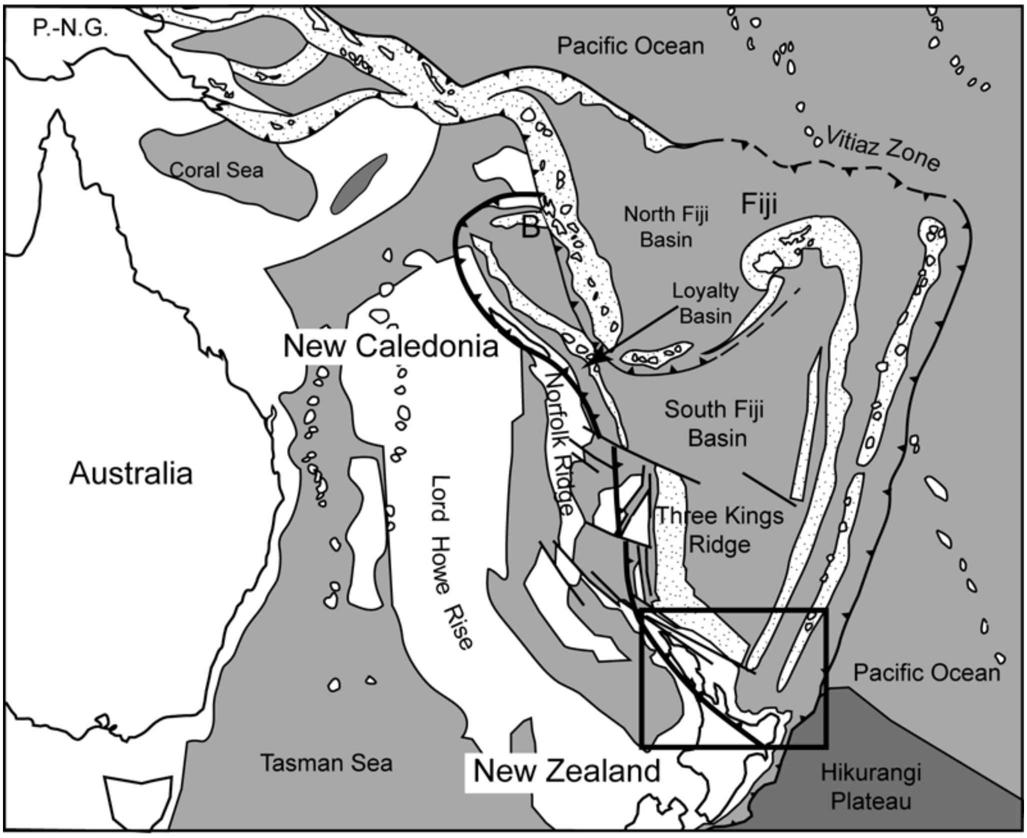

P.-N.G.
Pacific Ocean
Vitiaz Zone
Coral Sea
Fiji
North Fiji Basin
B
Loyalty Basin
New Caledonia
South Fiji Basin
Norfolk Ridge
Australia
Lord Howe Rise
Three Kings Ridge
Pacific Ocean
Tasman Sea
New Zealand
Hikurangi Plateau

Fig. 1

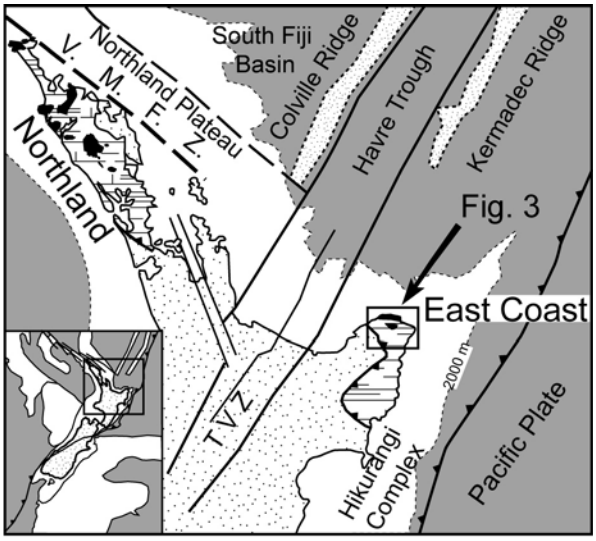
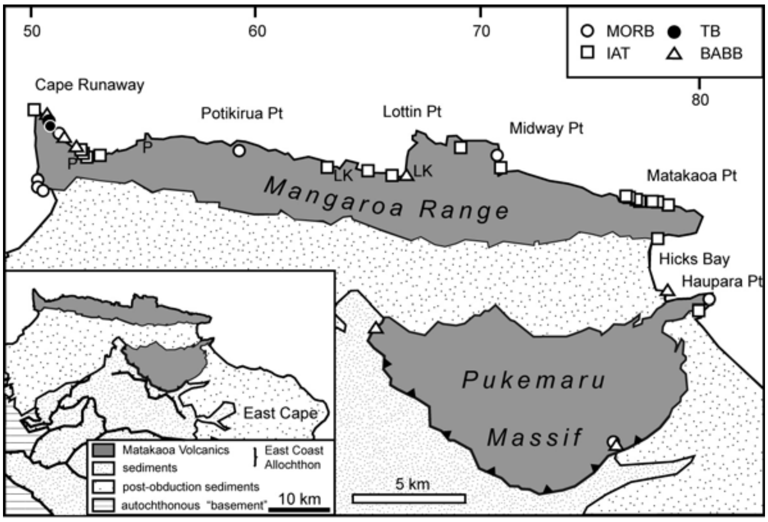
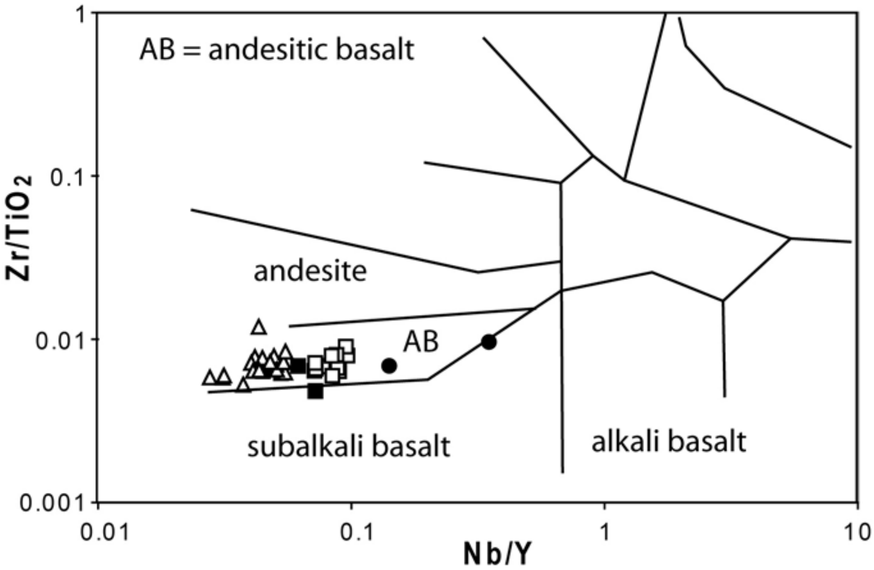

V.
M.
F.
Z.
Northland Plateau
South Fiji Basin
Colville Ridge
Havre Trough
Kermadec Ridge
Northland
Fig. 3
East Coast
2000 m
TVZ
Hikurangi Complex
Pacific Plate

Fig. 2



50
60
70
80
MORB
TB
IAT
BABB
Cape Runaway
Potikirua Pt
Lottin Pt
Midway Pt
Matakaoa Pt
Mangaroa Range
Hicks Bay
Haupara Pt
Pukemaru
Massif
East Cape
Matakaoa Volcanics
sediments
East Coast Allochthon
post-obduction sediments
autochthonous "basement"
10 km
5 km

Fig. 3



AB = andesitic basalt
andesite
AB
subalkali basalt
alkali basalt
Zr/TiO2
Nb/Y
1
0.1
0.01
0.001
0.01
0.1
1
10

Fig. 4

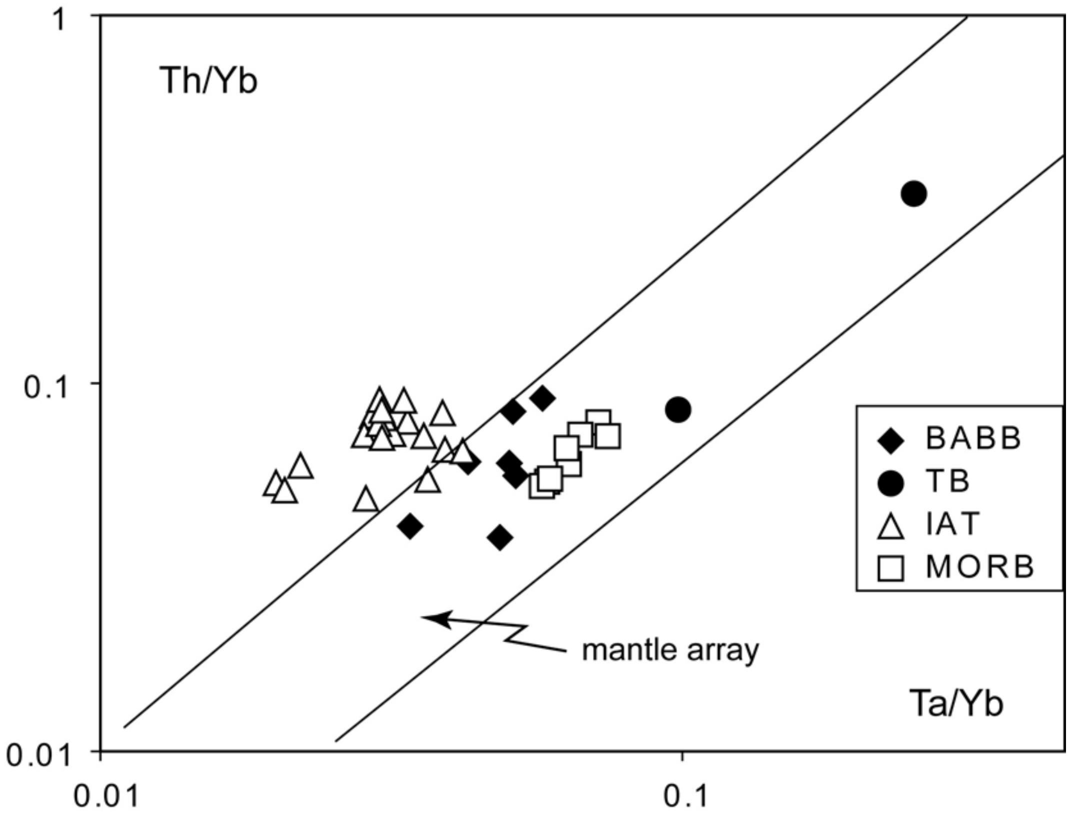
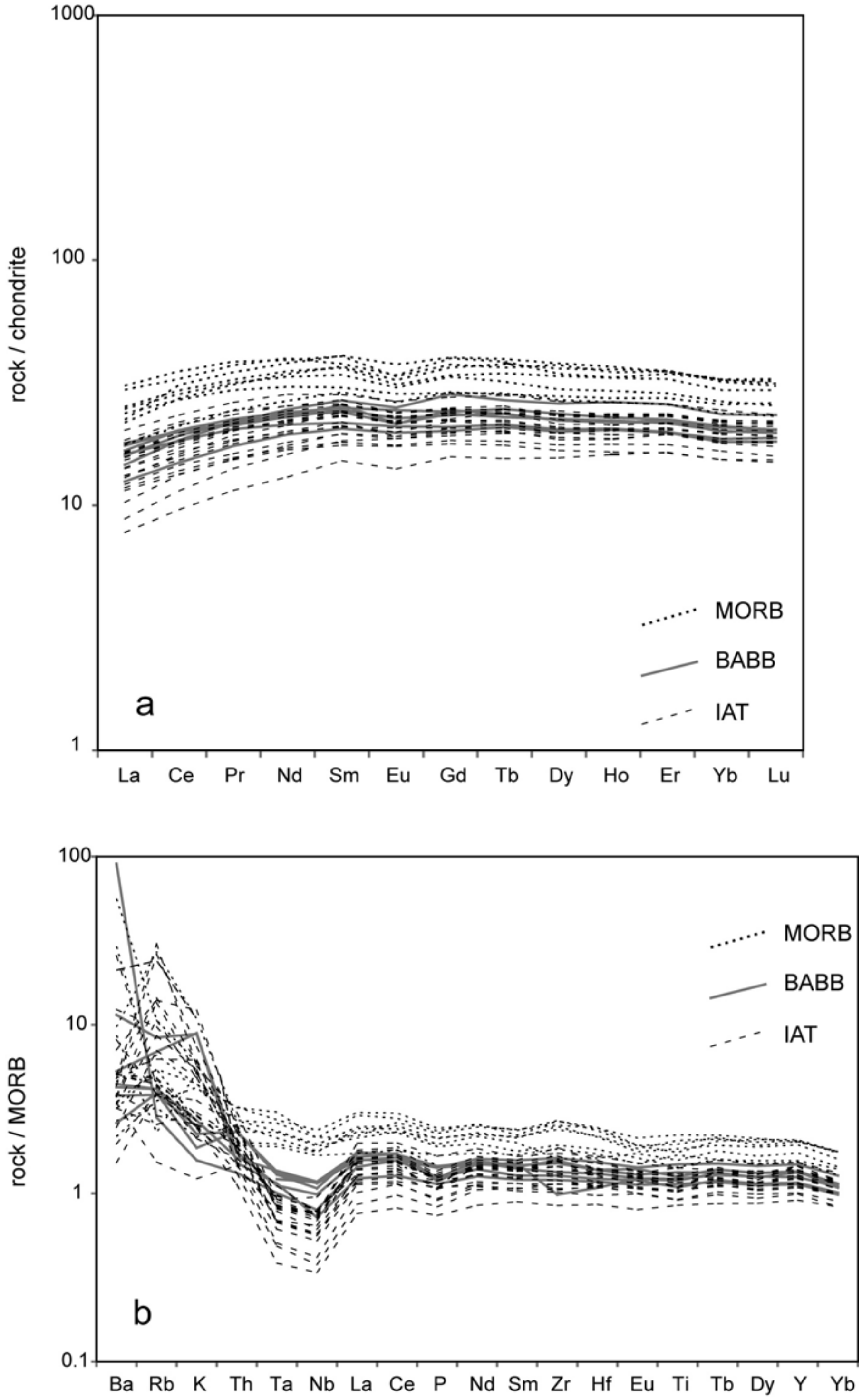
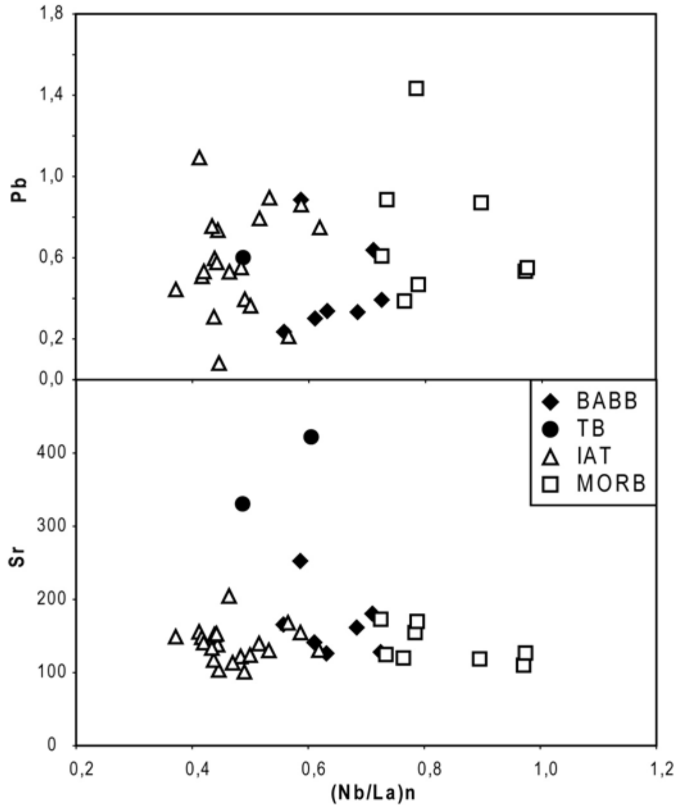


Fig. 5



rock / chondrite
1000
100
10
1
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Yb Lu
MORB
BABB
IAT
a
rock / MORB
100
10
1
0.1
Ba Rb K Th Ta Nb La Ce P Nd Sm Zr Hf Eu Ti Tb Dy Y Yb
b

Fig. 6


1,8
1,4
1,0
0,6
0,2
0,0
Pb
400
300
200
100
0
Sr
BABB
TB
IAT
MORB
0,2
0,4
0,6
0,8
1,0
1,2
(Nb/La)n

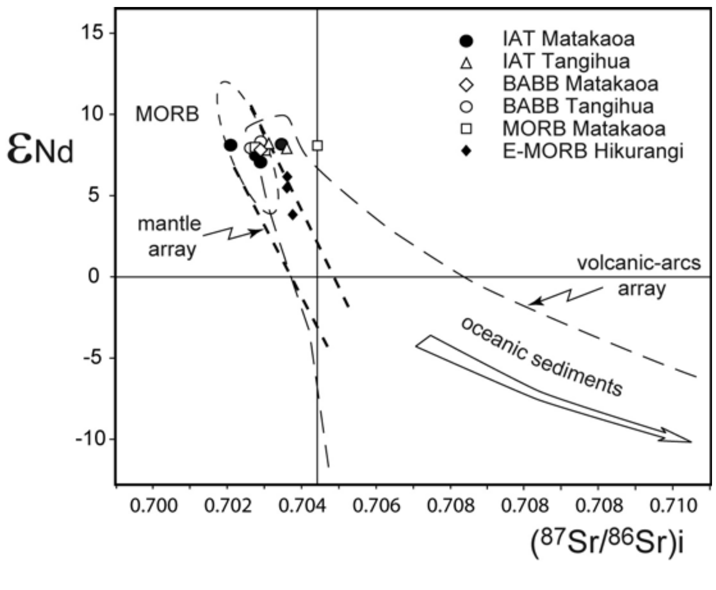
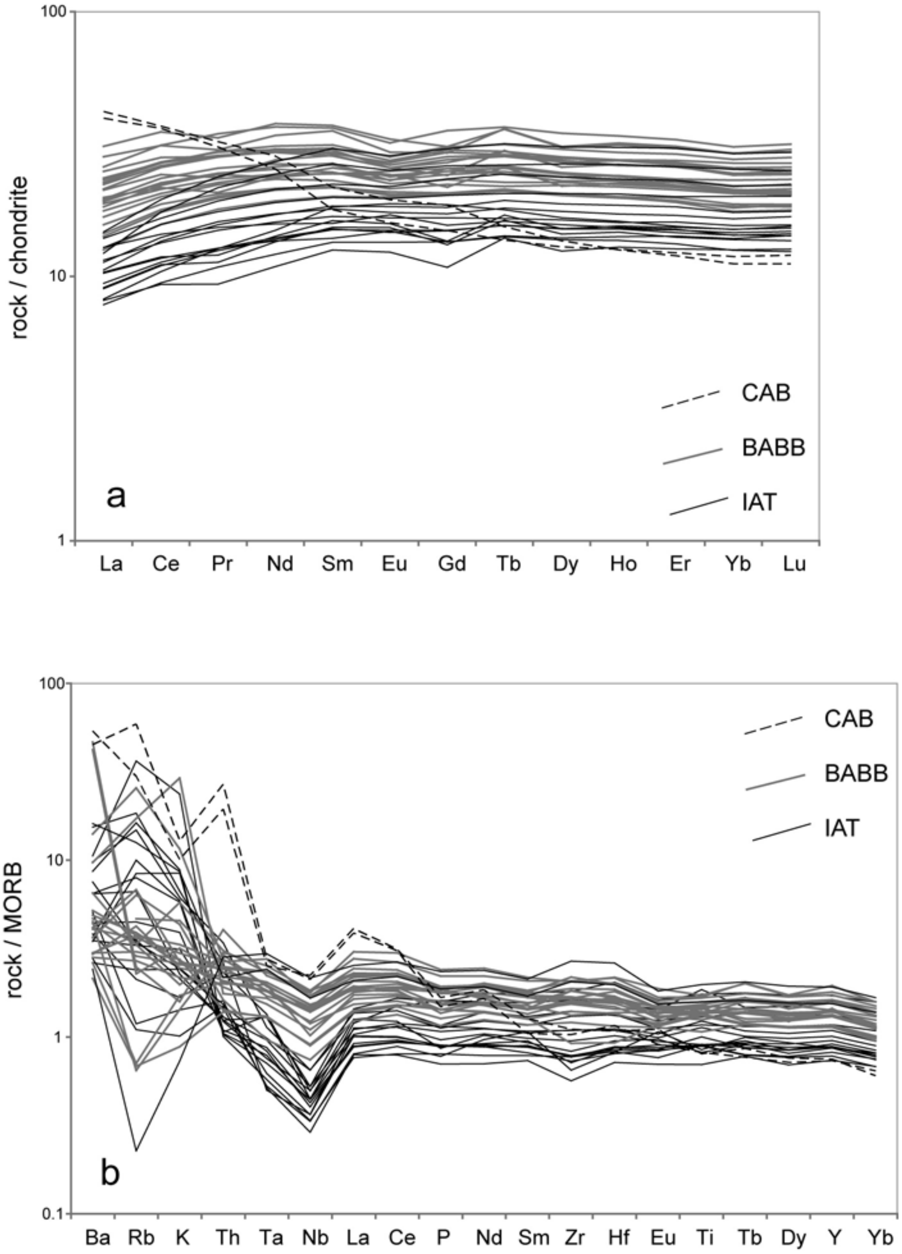
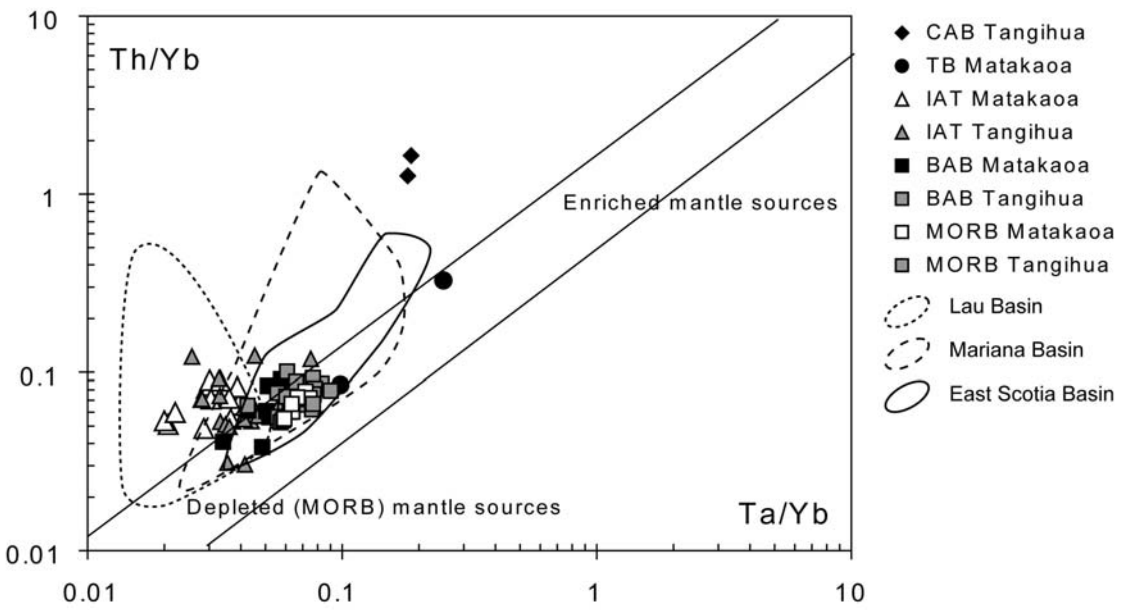

IAT Matakaoa
IAT Tangihua
BABB Matakaoa
BABB Tangihua
MORB Matakaoa
E-MORB Hikurangi
MORB
εNd
mantle
array
volcanic-arcs
array
oceanic sediments
15
10
5
0
-5
-10
0.700
0.702
0.704
0.706
0.708
0.708
0.708
0.710
(^{87}Sr/^{86}Sr)i

Fig. 7


100
10
1
rock / chondrite
a
CAB
BABB
IAT
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Yb Lu
100
10
1
0.1
rock / MORB
b
CAB
BABB
IAT
Ba Rb K Th Ta Nb La Ce P Nd Sm Zr Hf Eu Ti Tb Dy Y Yb



Th/Yb
Ta/Yb
10
1
0.1
0.01
0.01
0.1
1
10
Enriched mantle sources
Depleted (MORB) mantle sources
CAB Tangihua
TB Matakaoa
IAT Matakaoa
IAT Tangihua
BAB Matakaoa
BAB Tangihua
MORB Matakaoa
MORB Tangihua
Lau Basin
Mariana Basin
East Scotia Basin

Fig. 9

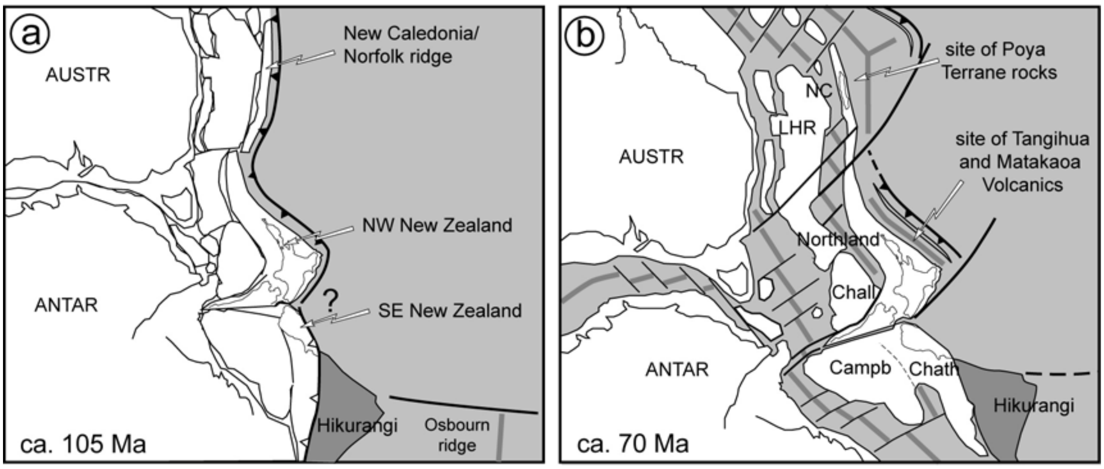
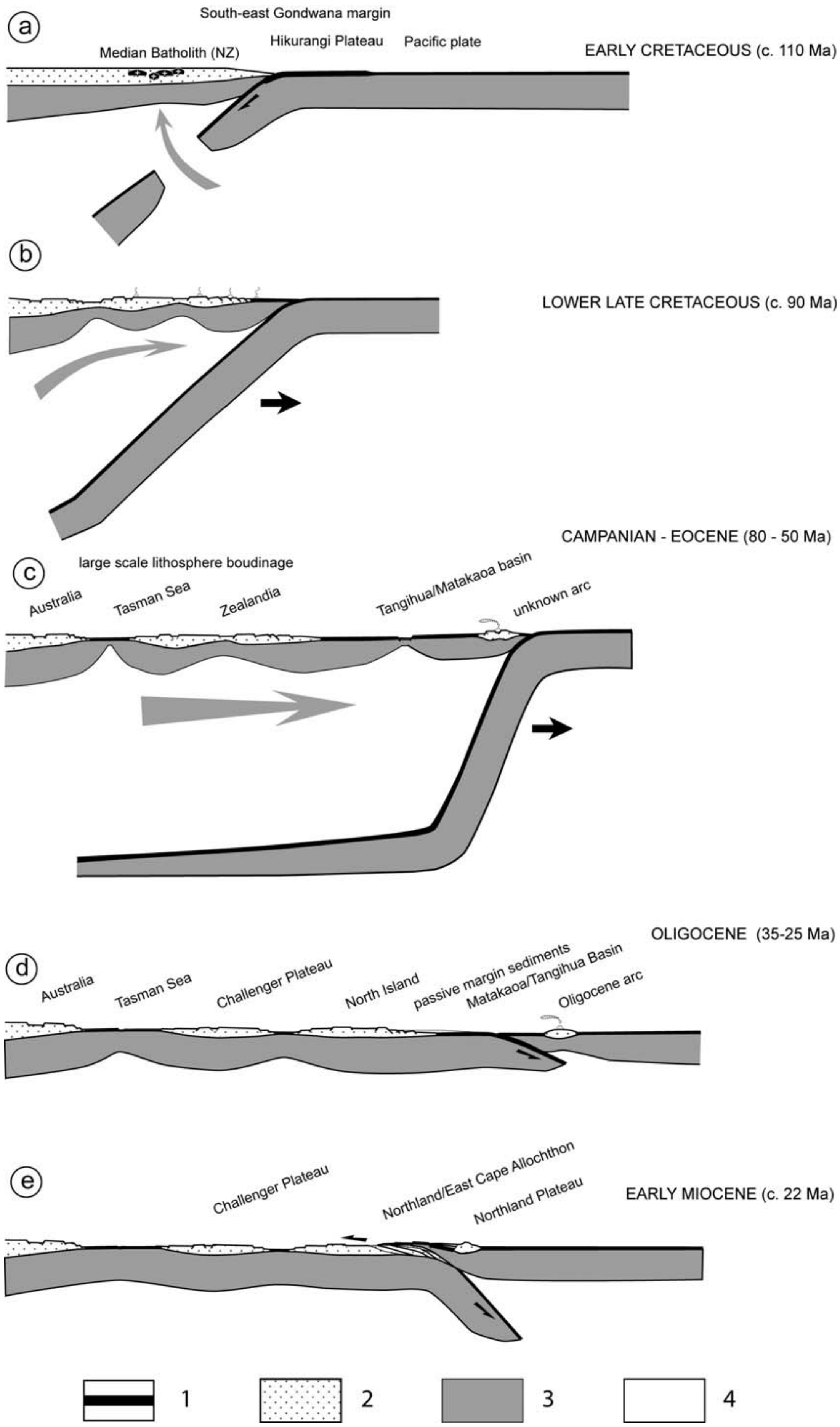

a
AUSTR
ANTAR
New Caledonia/
Norfolk ridge
NW New Zealand
?
SE New Zealand
Hikurangi
Osbourn
ridge
ca. 105 Ma
b
AUSTR
ANTAR
NC
LHR
site of Poya
Terrane rocks
site of Tangihua
and Matakaoa
Volcanics
Northland
Chall
Campb
Chath
Hikurangi
ca. 70 Ma

Fig. 10


a
South-east Gondwana margin
Median Batholith (NZ)
Hikurangi Plateau
Pacific plate
EARLY CRETACEOUS (c. 110 Ma)
b
LOWER LATE CRETACEOUS (c. 90 Ma)
CAMPANIAN - EOCENE (80 - 50 Ma)
c
large scale lithosphere boudinage
Australia
Tasman Sea
Zealandia
Tangihua/Matakaoa basin
unknown arc
OLIGOCENE (35-25 Ma)
d
Australia
Tasman Sea
Challenger Plateau
North Island
passive margin sediments
Matakaoa/Tangihua Basin
Oligocene arc
e
Challenger Plateau
Northland/East Cape Allochthon
Northland Plateau
EARLY MIOCENE (c. 22 Ma)
1
2
3
4